3 Corner Satellite:
New Mexico Final Technical Report

by

Stephen Horan

NMSU-ECE-02-005

THE KLIPSCH SCHOOL OF

ELECTRICAL AND COMPUTER ENGINEERING

TECHNICAL REPORT SERIES

AFRL-SR-AR-TR-03-

0001

3 Corner Satellite:

New Mexico Final Technical Report

by

Stephen Horan

NMSU-ECE-02-005

NMSU-ECE-02-005

3 Corner Satellite: New Mexico Final Technical Report

Stephen Horan
Manuel Lujan Space Tele-Engineering Program
New Mexico State University
Las Cruces, NM

Prepared for

Air Force Office of Sponsored Research
Arlington, VA

under Grant F49620-99-1-0194

November 24, 2002

Klipsch School of Electrical and Computer Engineering
New Mexico State University
Box 30001, MSC 3-O
Las Cruces, NM 88003-8001

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
24 Nov 2002

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
Jan. 1999 - Sept. 2002

4. TITLE AND SUBTITLE
3 Corner Satellite:
New Mexico Final Technical Report

5a. CONTRACT NUMBER

5b. GRANT NUMBER
F49620-99-1-0194

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Stephen Horan

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
New Mexico State University
Klipsch School of Electrical
And Computer Engineering
Lujan Space Tele-Engineering
Program
Box 30001, MSC 3-O
Las Cruces, NM 88003-8001

8. PERFORMING ORGANIZATION REPORT NUMBER
NMSU-ECE-02-005

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr. Gerald L. Witt
AFOSR/NE
4015 Wilson Blvd, Room 713
Arlington, VA 22203-1954
Program Manager
Physics & Electronics
Directorate

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Public Availability

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
As part of the overall 3 Corner Satellite (3CS) project within the University Nanosat Program, the development and testing of a communications subsystem for the satellite was undertaken at New Mexico State University in conjunction with the other team members. This report describes the overall satellite project and the details of the development of the flight radio system for 3CS. This report also documents the preliminary design of the LabVIEW software for linking the university ground communications network.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: UNCLASSIFIED			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	UL		19b. TELEPHONE NUMBER *(include area code)*

Contents

List of Figures

List of Tables

INTRODUCTION

Three Corner Satellite Description

The Three Corner Satellite (*3CS*) constellation is a cluster of three nanosatellites that are part of the US Air Force University Nanosat program. The *3CS* project was begun in January 1999 and the cluster of satellites is presently awaiting launch in 2003 from the Space Shuttle. The satellites are shown in their launch configuration in Figure. 1. The *3CS* project is a joint effort of the faculty, staff, and students at the participating universities: Arizona State University (ASU), the University of Colorado at Boulder (CU), and New Mexico State University (NMSU). Consult the [Unde 99], [Hans 99] and [Hora 99] for further details on the baseline design and mission concepts.

The *3CS* mission has four primary and three secondary objectives. The primary mission objectives include: stereo imaging, virtual formation flying, inter-satellite communications, and end to end command and data handling. The science will include imaging of clouds and other atmospheric structures using a satellite formation. After deployment, the three satellites will operate together using formation flying techniques. This will be accomplished while using virtual formation communications, a technology that allows the satellites to operate as a network utilizing communication and data links. Finally, the formation will use distributed and automated operations. This allows both individual nanosats and the entire formation to be reconfigured for optimum data gathering, command and control, and communication.

The secondary mission objectives include: validation of a MEMS heater chip for a Free Molecule Micro Resistojet (FMMR) propulsion system, demonstration of generic nanosatellite bus design, and student education.

One of the principal features of the *3CS* mission is that all three nanosats are based on a similar design. Each university has responsibility for different subsystems, and all components are designed to be common to each of the satellites. Each school's team is comprised of a faculty member and graduate and undergraduate students. Each school leads in its respective areas of expertise and on strengths proven on past projects as follows:

a. ASU - program management, systems, structures, electrical power, micropropulsion, integration and testing, safety, configuration management and quality assurance,
b. CU - science (imaging), command and data handling, mission operations, and
c. NMSU – communications.

Using this team concept, the design was developed at the lead school with review and comment by the partner schools. In addition to the design work, the team members needed to verify that all components, materials, and design features would pass the NASA flight safety reviews for launch from the Space Shuttle. This paper concentrates on the design of the satellites. Since the individual subsystems were produced by different partner members at each school, the overall set of components needed to be matched and integrated at final assembly.

The *3CS* satellites were designed and fabricated as three common satellites. The main differences are antenna placement, the inclusion of the FMMR test electronics on two cluster

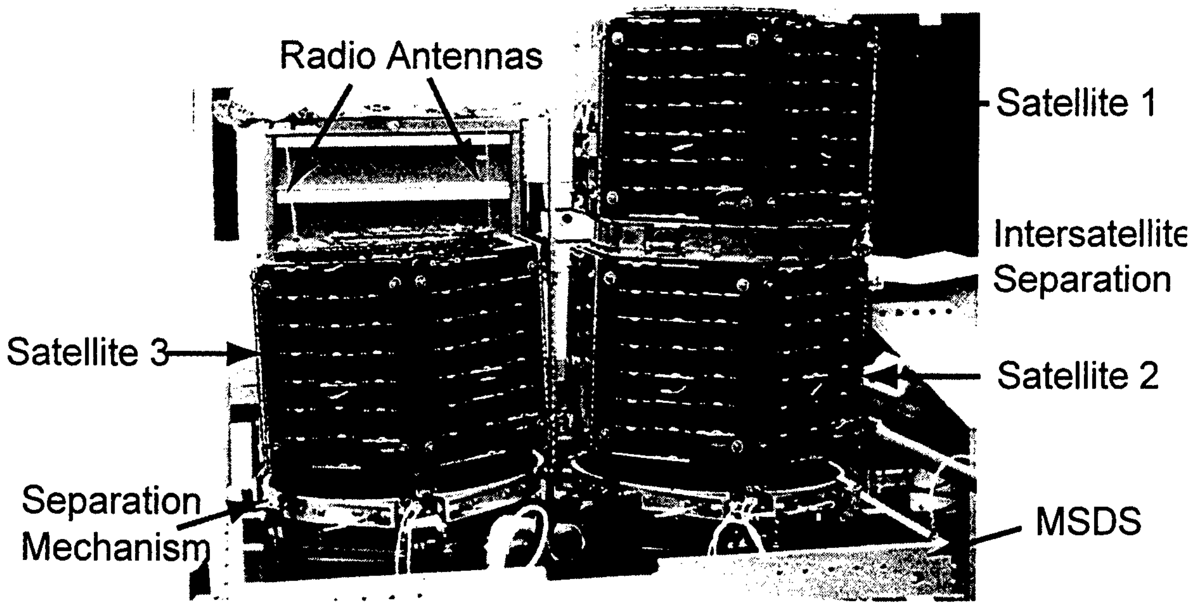


Figure 1 -- 3 Corner Satellite launch configuration.

members, and some additional solar cells on one satellite. In this section, we will describe the common components for each satellite necessary for the formation flying mission goals. This includes the structure, the power system, the end-to-end data system, the imaging system, and the communications system.

The structure for each satellite is based on a machined 6061-T6 aluminum isogrid structure as illustrated in Figure 2. The structure is hexagonal in cross section with the major axis for the satellite being 44.7 cm and the minor axis for the satellite is 39.4 cm. The height of each satellite is 29.2 cm. As can be seen in Figure 2, the side panels and the top and bottom plates form an interlocking structure. Brackets are added where the side panels abut for increased rigidity. The aluminum is anodized except for electrical contact points. The side and top panels are the load-bearing structure for the satellite. The structure was tested to verify that it would meet required strength and vibration mode requirements for a space shuttle payload.

The Electrical Power System (EPS) is composed of the following elements

a. solar cells,
b. battery pack,
c. inhibit relays,
d. DC/DC converter, and
e. microprocessor controller.

The system elements are organized as illustrated in Figure 3. The power from the battery and the solar cells is distributed as +5 V regulated and +12 V unregulated power. The 12-V power is used by the cameras and imaging electronics. The 5-V power is for other components. All systems but EPS have in-line switches controlled by EPS to prevent power-on prior to safe operating conditions being established after launch and to control the satellite power budget.

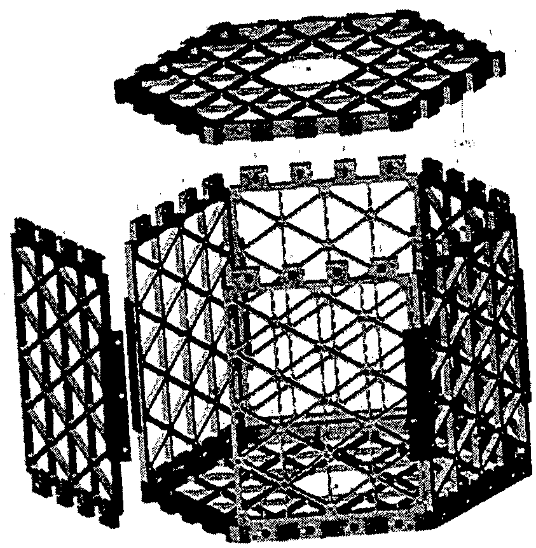


Figure 2 -- 3 Corner Satellite internal structures

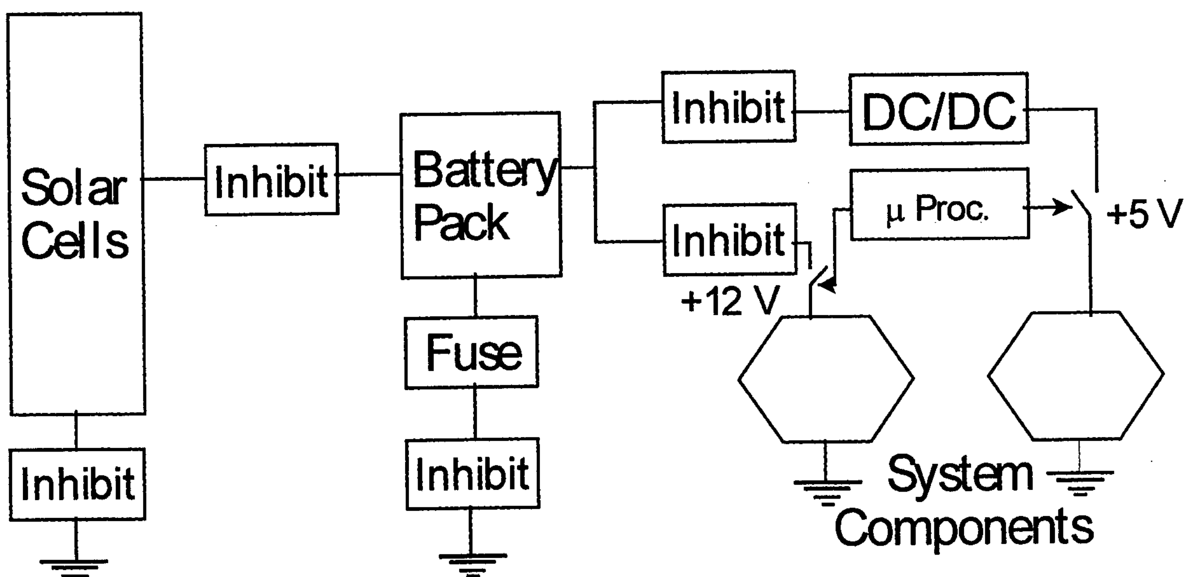


Figure 3 - *3CS* power system.

The EPS microcontroller is a PIC microcontroller with a watchdog timer. The EPS microcontroller is responsible for

a. sampling and storing health and welfare telemetry measurements,

b. listening for end-to-end data system commands to enable/disable individual components, and
c. acting as a watchdog timer for the end-to-end data system.

The inhibit relays are required to prevent premature energizing of the electronics during launch. There are three latching relays between each power source and the load. There is also one latching relay in the ground leg for each power source. These relays are set by the inhibit timer electronics in the MSDS portion of the launch configuration.

The solar panels use dual-junction gallium arsenide solar cells that are commercially manufactured. The side panels and top panel of each satellite holds the solar panel structure in place. Each panel consists of two strings of nine cells with each cell generating approximately 2.4 V. The solar panel contains a current meter and diode protection. The solar panel configuration is shown in the left half of Figure 4

The battery portion of the EPS is composed of a pack of ten NiCd cells with 2300 mAh of capacity. The battery is illustrated in the right half of Figure 4 which shows the packaging into a vented box with absorbent material to mitigate any leakage effects.

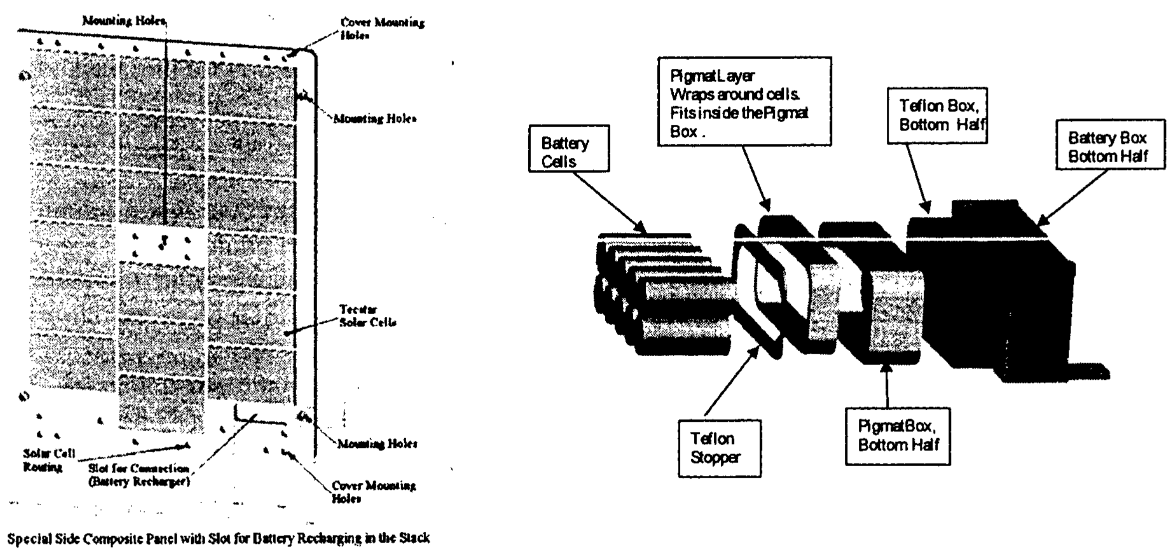


Figure 4 -- *3CS* solar cell and battery configuration.

he End-to-End Data System (EEDS) is an integration of computer hardware, software, procedures, and personnel for cluster command and control and data handling. The hardware component in each satellite includes an 823 Power PC flight computer having 16 MB of RAM, 8 MB of RAM organized as a solid state recorder, and a critical decoder for processing initialization commands.

The software is stored on disk and in ROM. The flight software is disabled until after deployment from the MSDS. The software uses a commercial operating system (VxWorks) and extensive use of commercial software tools for controlling the satellites. The primary tool is the System Control Language (SCL) to program rules to monitor the health and welfare of the satellite. The current state of the satellite can initiate scripts to take counter measures for detected faults. The rules can also be used to generate scripts to perform specific functions, e.g. initialize the radio system or the imaging system. Operational science events such as taking a sequence of pictures are also SCL-based activities.

The command structure for the satellites is based on specific files sent from the ground stations, inter-satellite messages, and pre-stored, timed commands. The scheduling software can build a sequence of operational commands to be executed between ground station contact times.

The imaging system for the satellites is based on four cameras per satellite with the goal of producing images of clouds from orbit. There are two cameras on the top bulkhead and two cameras on the bottom bulkhead. The cameras interface with EEDS for data and EPS for power. The cameras are commercial cameras using a 640 x 480 pixel CMOS sensor. The cameras have full automatic exposure control. The on-board algorithms will be used to evaluate image quality and prioritize the images for downloading. The imaging cameras are illustrated in the right portion of Figure 5 and the mounting in the bulkhead in shown in the left portion of Figure 5.

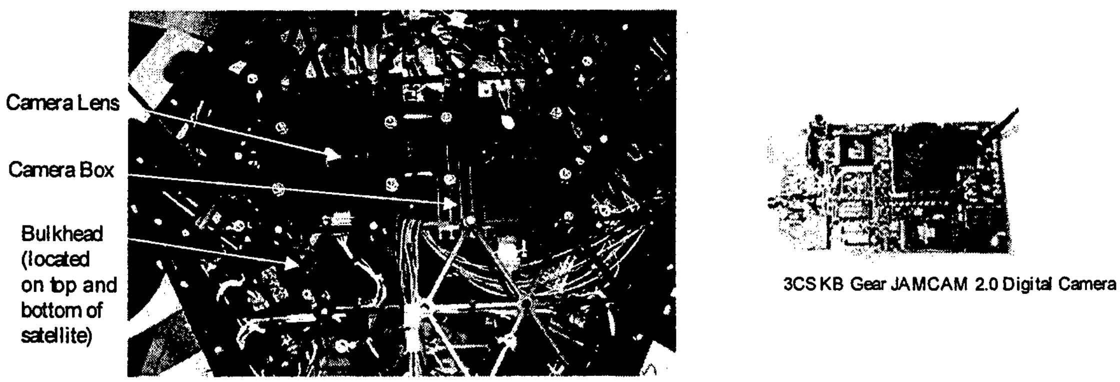


Figure 5 -- *3CS* imaging system.

The communications system is based on commercial amateur radio hardware that has been modified for an extended frequency range outside the amateur bands. The radios are arranged as a dual redundant flight radio in each satellite. Each radio is software programmable via the EEDS to set frequency, power, and operating characteristics. The radios are only powered on when supplied power by the EPS to help control the overall satellite power budget with each radio being individually powered. The nominal operating mode will be to have one radio on at all times in receive mode to listen for commands. The radios use a VHF frequency for the data downlink, UHF frequency for the command uplink, and a different UHF frequency for the inter-satellite crosslink communications. All communications use a frequency shift keying technique and the AX.25 packet communications protocol at the physical channel level. The data rates available on the radios are 1200 bps and 9600 bps. The maximum transmission power is 1 W.

The antenna system uses a commercial dual-band antenna for each radio. The antennas on the two satellites that are joined in the 2 x 1 launch configuration have their antennas inserted into a sheath inside the other satellite for launch. Upon satellite separation, the antennas are withdrawn from the sheaths without use of a deployment mechanism.

The primary ground control station will be at CU. The other schools (ASU and NMSU) will have compatible ground stations to be used as backup relay points for both commands and telemetry by using store and forward data files in either direction. The uplink data files can be commands, schedules, or revised software. The relationship between the satellites and the ground stations is illustrated in Figure 6.

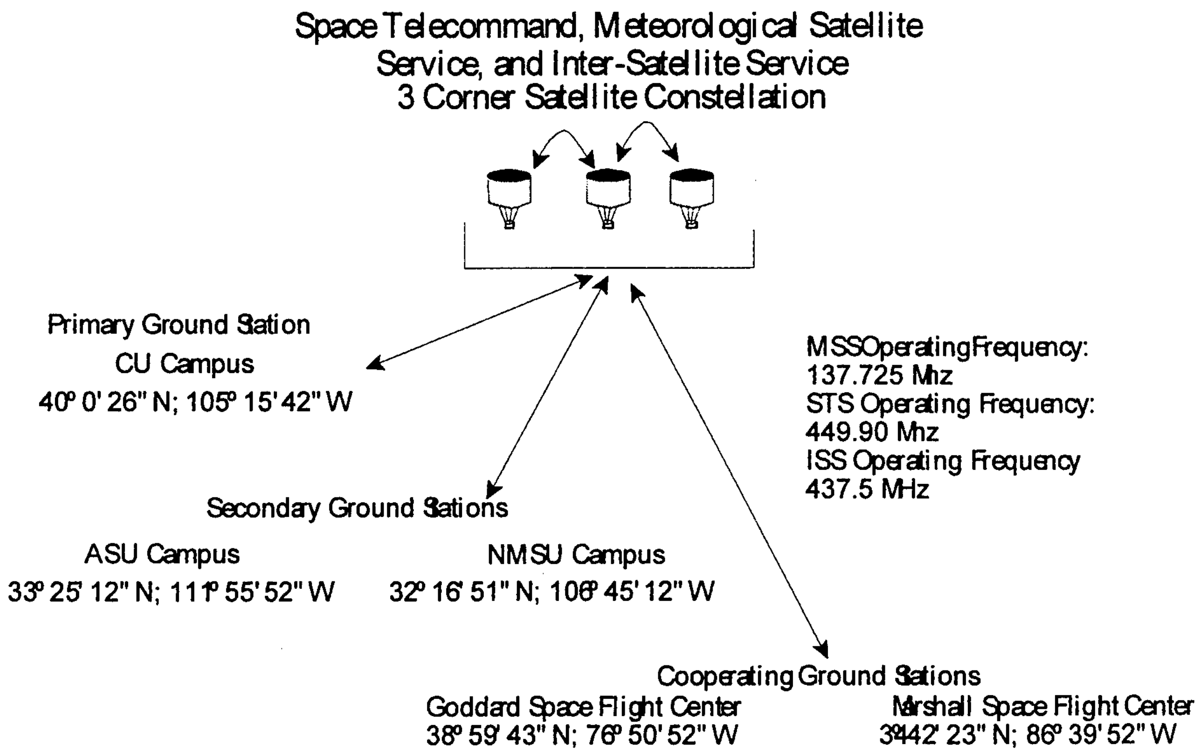


Figure 6 -- *3CS* communications links.

The satellite cluster launch configuration was shown in Figure 1. The 2x1 satellite configuration was determined by vibration limits on the satellite separation systems. This configuration consists of

a. the individual satellites
b. the Lightband inter-satellite separation mechanism between the two joined satellites
c. the Starsys separation mechanism between the launch plate and the satellite on it
d. the Multiple Satellite Deployment System (MSDS) that holds the cluster configuration.

For the purposes of this project, the Lightband, Starsys, and MSDS components are "government furnished equipment" and outside the control of the *3CS* project team. However, the satellites need to be compatible with the components. Additionally, the timer control and power for removing the inhibits are controlled through the MSDS electronics. The electronic signals for activating the satellites are passed through the Starsys and Lightband components to the cluster members. This integrated system is delivered to NASA to be mated with the NASA systems for launch.

Scope

The remainder of this report deals with the development of the *3CS* communications system for the actual flight system. The initial report for this project included a copy of the MSEE Thesis from Mr. Bobby Anderson that provided an initial design for the communications system. This final report describes the "as-built" communications subsystem for the satellites.

Topic Development

The next section is the detailed description of the flight radio development. In it, we discuss the design constrains and limits on developing the hardware, the testing to validate the components, and the production of the actual flight units. For the full details of the design, consult the documentation supplied with the flight units.

The Appendices hold the three papers on the development of the system that were presented at conferences this year.

FLIGHT COMMUNICATIONS SYSTEM DESIGN

To produce a flight radio system that would be usable across all three satellites, we needed to base the design on a tight set of constraints and design goals. The following paragraphs indicate the system constraints and the design goals for the flight radio.

Constraints

The largest constraint on the radio design was imposed by the power system. The total power budget for each satellite was expected to be approximately 10 W. From this, communications would be allocated 5 W from a regulated, 5-V power bus on a shared basis with other subsystems since communications would not be active at all times. The requirement for the radio system was that it operate with an input voltage of 5 V and draw no more than 1 A when operating. Due to inefficiencies and the slim power margins to begin with, it was not considered effective to use a DC-DC converter to raise the input voltage to a higher level.

The next constraint was that the radio system would need to support command services, downlink services, and inter-satellite services. The intention was to use the available allocations in the UHF and VFH bands, respectively, for the first two services. The inter-satellite service would be run as an amateur radio experiment utilizing packet radio and APRS techniques. The minimum data rate for the command and inter-satellite services would be 1200 bits per second while the minimum data rate for the telemetry data would be 9600 bits per second.

The solution for the flight radio system would need to meet the *3CS* size and weight constraints. While this never became a major issue, the overall design team tried to minimize weight whenever possible because the satellite stack was always close to its maximum allowed weight based on launch constraints.

Any system that was chosen would need to pass qualification testing. The radio system would be designed to survive the Hitchhiker vibration qualification testing. [NAS 99] The radio would also need to survive thermal cycles from -20° C to + 60° C.

One design constraint that was explicitly not imposed was for the components to be radiation hardened. This decision was made, primarily, because the expected lifetime of the satellites on orbit would be only a few months. Given this short expected mission lifetime, it was decided not to expend the extra cost for explicit radiation hardening. The project team decided that between having the radios mounted in aluminum boxes, the use of a redundant configuration, and the ability to reset the radios via the flight computer, the risk of total failure due to radiation effects would be small enough to warrant using commercial-grade parts.

Goals

The first design goal was to provide for all of the radio services in a single unit rather than having frequency-specific radios. This would help minimize weight and total power consumption. If a single radio could be used, a secondary design goal would be for the flight radio subsystem to provide a software control of frequency settings and radio parameters that would be under the control of the flight computer that would be scheduling operations. The final design goal was to provide for a redundant design to allow for a graceful failure of the flight radio subsystem. The frequencies chosen for the actual transmissions as requested on the DD1494 form submitted to the Air Force spectrum management office and the Federal Communications Commission are listed in Table 1.

Table 1 – Requested Frequencies for the 3 Corner Satellite Project.

Frequency	Usage
137.725 MHz	Data downlink (telemetry and images)
449.90 MHz	Command uplink
437.5 MHz	Inter-satellite service

Design Solution

The design of the flight radio was based on an existing commercially-available product. The following paragraphs describe why the components were chosen and how the components were modified for flight.

Radio Choice

Based on the design constraints, the Kenwood TH-D7 transceiver was chosen as the basis for the *3CS* flight radio. The following features were key to selecting this particular model:

a. The radio would operate with a 5 V supply voltage and consume approximately 1 A of current at the highest power mode
b. The radio has two lower power settings thereby allowing for power control options
c. The radio has a standard RS-232 interface for data and control
d. The radio has an integrated modem thereby eliminating the need for an external modem. The radio also provided internal support for packet communications modes that can be customized by commands from the flight computer.
e. The radio could be easily modified for the UHF and VHF services required. The radio had built-in support for the inter-satellite link.

An additional feature that was found to be useful was that the TH-D7 stores its settings to memory so that they are not lost when the radio is powered off. This implies that the flight software does not need to re-load settings each time. However, this would remain an option to help recover from single-event upsets.

Because the basic radio components were relatively light when removed from the commercial housing, we proceeded to design a system with two TH-D7 units to form a redundant flight radio subsystem. The necessary modifications are next described.

Necessary Modifications

Because the TH-D7 was intended for a commercial market, it has a number of components that would either be unnecessary in a flight radio (speaker and microphone) or not allowed (zinc alloy plate and various plastics). By using an iterative process, a procedure was developed to exactly modify the radio to first maintain functionality and second to eliminate all components that were not necessary for flight or had to be modified to pass materials compatibility. The main materials problem was with the zinc alloy chassis plate used in the radio. This was replaced by an equivalent aluminum plate of the same form factor. The procedure was codified into a step-by-step procedure to be used in preparing the actual flight radios [Hor 01a]. Figure 7 illustrates an exploded view of the initial radio components and the ones finally kept in the flight units. The circuit boards were conformal coated and held together with staking compound and lacing cord as shown in Figure 8. The main functional modification to the radio was to wire it to always to be "on" so that it would be operational whenever power was applied.

During testing of the radio's performance, we discovered that the manufacturer-supplied dual-band antenna did not perform well at VHF frequencies. The performance was 10 dB below that of a tuned blade antenna for the VHF frequency. We replaced the stock dual-band antenna with a different commercial dual-band antenna that was only 5 dB below the tuned blade performance at VHF and within 1 dB of tuned blade performance at UHF.

Redundant Design

One of the design goals was to produce a redundant flight radio sub-system for the *3CS* satellites. The design was realized by using two TH-D7's in a primary and backup configuration. Each radio would individually receive power only when the power sub-system was commanded to do so by the flight computer. Each radio was individually addressable by the flight computer through its RS-232 data port. Each radio uses its own dual-band antenna (no antenna cross switching). A Basic Stamp microcontroller was added to the design to ensure proper radio power up. Through testing, we found that on occasion, the TH-D7 would not properly initialize when power was first applied. The microcontroller monitors the input line to determine when the radios are powered. If the microcontroller detects that power has been applied to the radio but the radio does not activate, then the microcontroller strobes the corresponding TH-D7 to emulate a user cycling the on/off switch. We have found that the radio will properly activate after this procedure. A separate circuit board was designed and fabricated for the microcontroller and added to the overall flight radio design.

Each subsystem in the *3CS* design is housed in its own aluminum box to provide low-level radiation shielding and to provide some radio frequency isolation and minimize interference between subsystems. The flight radio is no exception. The housing for the flight radio was designed to hold both TH-D7 radio circuit boards and the microcontroller circuit board. After assembly, the radio units were delivered to ASU for integration with the other satellite components.

The wiring diagram for the redundant configuration is illustrated in Figure 9 and one of the flight units being assembled with its aluminum housing is illustrated in Figure 10. A manual for the integrated design was produced to guide software developers and for operations training. [Hor 02]

Design Validation and Testing

To validate the design, an extensive test program was developed to ensure that no functionality was lost as the radios were modified, assembled into the flight units, and then delivered for integration into the satellite. The first step in the process was to start with the Manufacturer's

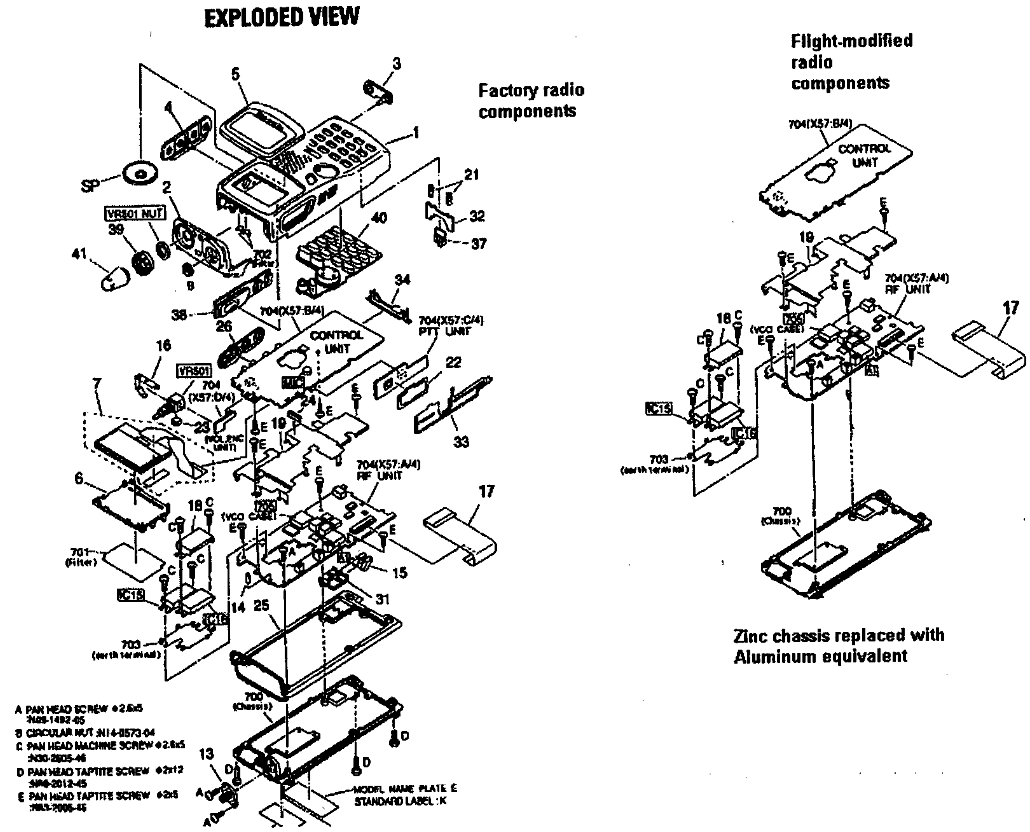


Figure 7 -- Original TH-D7 components and the parts kept for the flight radio subsystem.

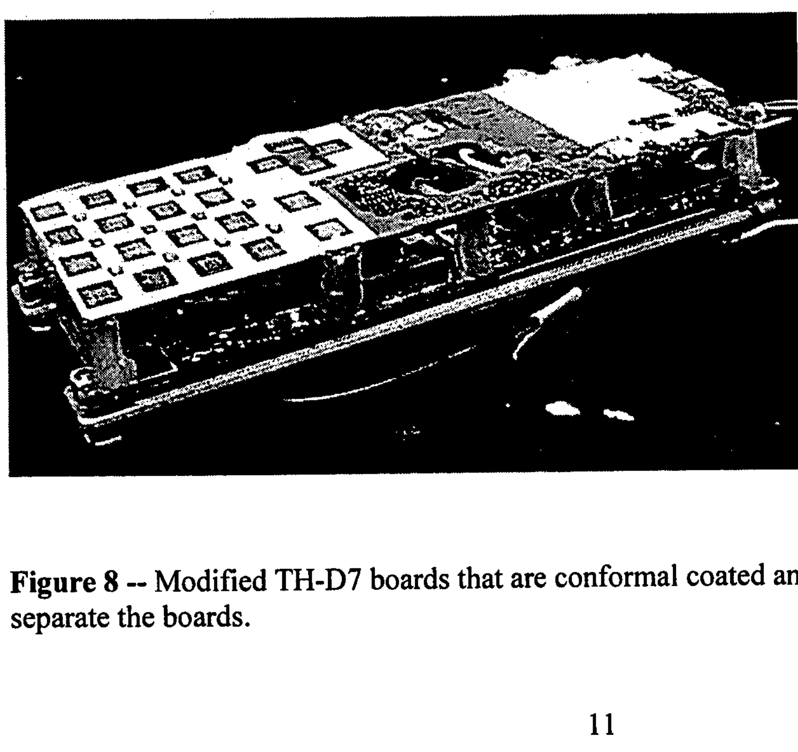


Figure 8 -- Modified TH-D7 boards that are conformal coated and use staking compound to separate the boards.

Cable and Wiring

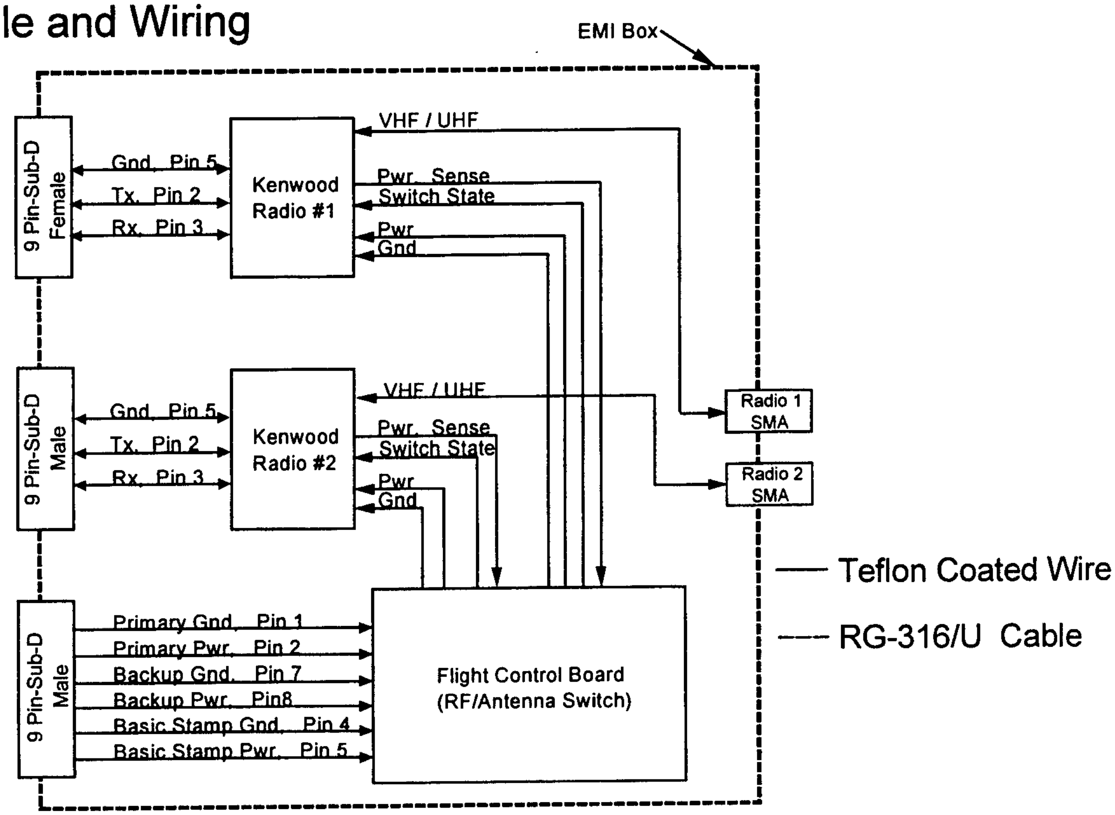


Figure 9 -- Wiring diagram for the flight radio components.

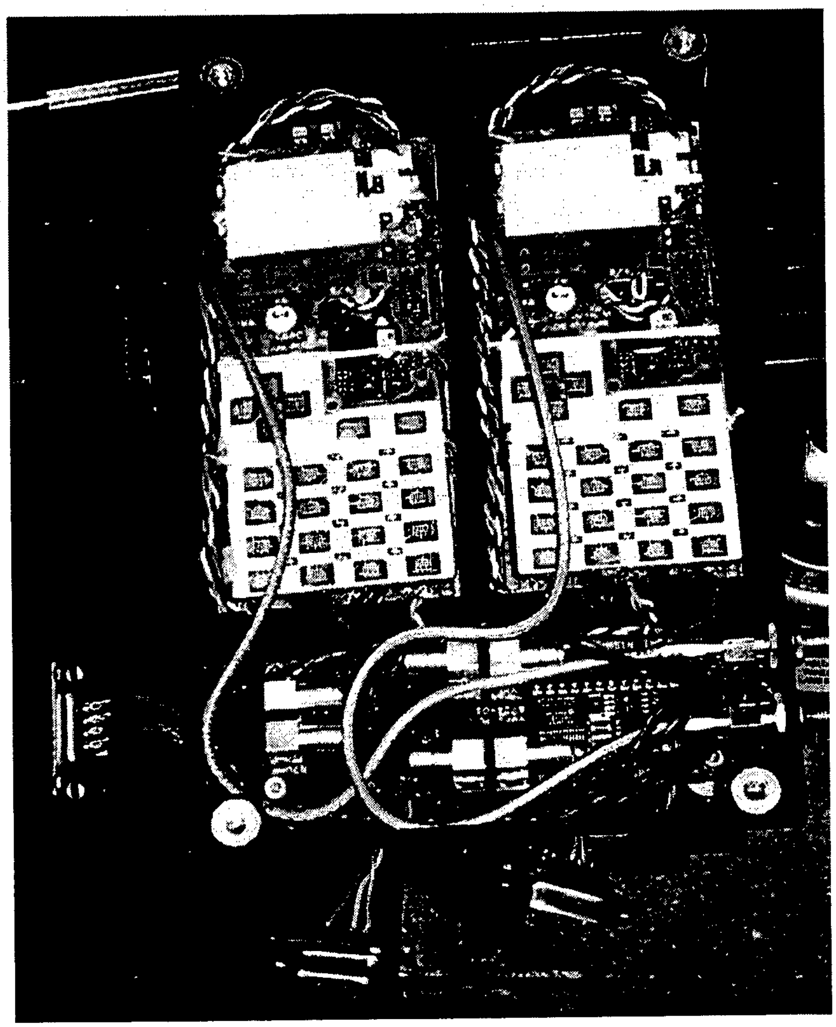


Figure 10 -- *3CS* flight radio components.

Acceptance Test Plan where the required functions were tested, operational voltage and power confirmed, and radio transmission format and power were validated [Hor 01b]. This test was derived from extensive experimenting with the radio's performance and developing automated scripts that would exercise the radio's set up and configuration. This test became the baseline for subsequent functional and characterization testing. The test sequence was also used to illustrate how the radios could be programmed for the software development team. After the electronics on each TH-D7 were modified, and before assembling into the flight unit, the individual unit was tested for proper functionality. This test was then performed again after flight unit assembly. This test procedure could then be re-run after other testing to validate proper functionality.

To validate that the flight radio would pass acceptance testing, an engineering unit was produced and subjected to thermal cycle testing and vibration testing. The vibration testing was at full shuttle qualification levels. A visual inspection and a test for proper functionality were performed after the vibration testing to ensure that the units survived.

Finally, a link analysis was performed to ensure that link closure would be possible with the radio system [Hor 00]. While link closure is possible, it may not be possible to downlink an entire uncompressed image during a single pass to a single ground station. It may be required to have several ground stations receive the image segments and then re-integrate the image in software.

GROUND COMMUNICATIONS NETWORK

A design is currently underway to link the universities in the *3CS* team to allow the transmission of data between the ground stations. This software is being developed in the LabVIEW environment and currently undergoing testing. The baseline description is given in [Mau 02] which is included in the Appendix to this report.

The requirements for the ground networking software are given in Table 2. These are realized as a set of Virtual Instruments (VI) in the LabVIEW code. Much of this code is based upon the VIs developed for unit testing the flight radios at NMSU.

To date, the basic testing of this software has shown that the students at the University of Colorado can control the computers at New Mexico State University. Further testing will continue.

Table 2 – Ground Networking Software Requirements	
No.	**Requirement**
GND.1	The Ground Communications network shall support a minimum of three remote ground stations from a control station
GND.1.1	The Ground Communications network will provide a means to remotely initialize each remote ground station
GND.1.1.1	The initialization process will include a means to remotely configure the TNC at each remote ground station
GND.1.1.2	The initialization will include a means to remotely iniate the tracking functions at each remote ground station
GND.1.2	The Ground Communications network will provide a means to monitor the status of the remote ground stations
GND.1.2.1	The status monitoring function will include a means to monitor the status of the link between the control station and the remote station
GND.1.2.2	The status monitoring function will include a means to monitor the number of bytes of data received at the remote terminal on the radio return link
GND.1.3	The Ground Communications network will provide data transfer between each remote terminal and the central control station
GND.1.3.1	The data transfer function will include the ability to transfer data in real time
GND.1.3.1.1	The real time data transmission will have the means to send data in real time from the control station to each remote terminal
GND.1.3.1.2	The real time data transmission will have the means to send data in real time from each remote ground station to the control station
GND.1.3.2	The data transfer function will include the ability for store-and-forward data transfer
GND.1.3.2.1	The store-and-forward data transmission will have the means to send data from the control station to each remote terminal for later transmission to the satellites
GND.1.3.2.2	The store-and-forward data transmission will have the means to record satellite data at each remote terminal for later transmission to the control station in the event that the internet link goes
GND.2	The control station and the remote terminals shall have synchronized clocks
GND.3	The Ground Communications network shall have security measures that protect unauthorized use of system
GND.3.1	The security measures will prevent an unwanted party from having access to the control terminal
GND.3.2	The security measures will prevent an unwanted party from having access to the remote ground stations
GND.4	The Ground Communications network software will be capable of execution on current Windows (98/NT/2000/XP), Unix, Macintosh, and Linux operating systems.

CONCLUSIONS

A commercial-grade device can be readied for space flight and tested to pass basic safety and materials concerns. The usual engineering lessons of adequate documentation, well-specified procedures, and traceable performance become especially important when teaching students and when performing a distributed design. As might be expected, more time is actually spent on this type of paperwork activity than on actual design work. However, good documentation and good practices make the ability to work together across school boundaries an achievable goal.

The utilities and capabilities of the LabVIEW programming environment can be used to form the basis for networking the three universities in the *3CS* team.

REFERENCES

[Unde 99] Underhill, B., et al. "Three Corner Satellite Constellation - Arizona State University: Management; Electrical Power System; Structures, Mechanism, Thermal and Radiation; Attitude/Orbit Determination and Control; ASU Micropropulsion Experiment; and Integration," *Proceedings of the 13th Annual AIAA/USU Conference on Small Satellites,* SSC99-III-1, Logan, UT, August, 1999.

[Hans 99] Hansen, E., et al. "Three Corner Sat Constellation: C&DH, Stereoscopic Imaging, and End-to-End Data System," *Proceedings of the 13th Annual AIAA/USU Conference on Small Satellites*, SSC99-IV-1, Logan, UT, August, 1999.

[Hora 99] Horan, S., et al., "Three Corner Satellite Constellation - New Mexico State University: Communications, LEO Telecommunications Services, Intersatellite Communications, and Ground Stations and Network," *Proceedings of the 13th Annual AIAA/USU Conference on Small Satellites,* SSC99-VI-7, Logan, UT, August, 1999.

[NAS 99] National Aeronautics and Space Administration, *Hitchhiker Customer Accommodations & Requirements Specifications*, 740-SPEC-008, Goddard Space Flight Center, 1999.

[Hor 00] Horan, S., "3 Corner Satellite Communications Link Estimates," UN2-RPT-31114-403, Rev.a, Las Cruces, NM, 2000.

[Hor 01a] Horan, S., Alvarez, L., and Silva, A., "Assembly Procedure - Dual Transceiver," UN2-PLN-31114-417, Rev. a, Las Cruces, NM, 2001.

[Hor 01b] Horan, S., Alvarez, L., Jourdan, M., and Silva, A., "Manufacturers' Acceptance Test Procedure," UN2-RPT-31114-423, Rev.a, Las Cruces, NM 2001.

[Hor 02] Horan, S., Alvarez, L., Anderson, B., Pachecho, R., and Jourdan, M., "Dual Transceiver User's Manual," UN2-MAN-31114-404, Rev.B, Las Cruces, NM, 2002.

[Mau 02] K. Mauldin, "Networking Satellite Ground Stations Using LabVIEW," *Proc. International Telemetering Conference*, 02-10-4, San Diego, CA, October 2002.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

3CS	Three Corner Satellite
ASU	Arizona State University
CU	Colorado University
EEDS	End-to-End Data System
EPS	Electrical Power System
FMMR	Free Molecule Micro Resistojet
MSDS	Multiple Satellite Deployment System
NASA	National Aeronautics and Space Administration
NMSU	New Mexico State University
UHF	Ultra High Frequency
VI	Virtual Instrument
VHF	Very High Frequency

APPENDIXES

APPENDIX 1 – S. Horan and L. Alvarez, "Preparing a COTS Radio for Flight - Lessons Learned from the 3 Corner Satellite Project," *Proc. 16th Annual/USU Conference on Small Satellites*, SSC02-X-4, Logan, UT, August 2002.

APPENDIX 2 – S. Horan, et al., "The Three Corner Satellite Mission," Proc. International Symposium Formation Flying: Missions & Technologies, Toulouse, FR, October 2002.

APPENDIX 3 – K. Mauldin, "Networking Satellite Ground Stations Using LabVIEW," *Proc. International Telemetering Conference*, 02-10-4, San Diego, CA, October 2002.

Preparing a COTS Radio for Flight - Lessons Learned from the 3 Corner Satellite Project

Stephen Horan and Lawrence Alvarez
Klipsch School of Electrical and Computer Engineering
New Mexico State University
Box 30001, MSC 3-O
Las Cruces, NM 88003
Phone: (505) 646-4856; (505) 646-1478
e-mail: shoran@nmsu.edu; lalvarez@nmsu.edu

Abstract. As part of the 3 Corner Satellite program, a commercial-grade amateur radio transceiver was adopted to be the main flight radio due to power, weight, and time constraints. While this particular item was not designed for space use, it did have features that would make it useful in the 3CS mission. In this paper, we will review the decision process that led us to choosing the radio and describe the process of modifying the radio for flight. This includes issues related to materials, modifications necessary to the radio to make it acceptable, the qualification testing required, and the validation that performance quality was not significantly lost in the process. During this process, we discovered that the radio can be made acceptable to the flight safety process provided that a thorough understanding of the components is achieved and a great deal of experimentation is done before hand to characterize the radio.

Introduction

The *Three Corner Satellite* (*3CS*) constellation is a cluster of three nanosatellites that are part of the US Air Force University Nanosat program. The *3CS* project was begun in January 1999 and the cluster of satellites is presently awaiting launch in 2003 from the Space Shuttle. The satellites are shown in their launch configuration in Figure 1. The *3CS* project is a joint effort of the faculty, staff, and students at the participating universities: Arizona State University (ASU), the University of Colorado at Boulder (CU), and New Mexico State University (NMSU). Consult the references for further details on the baseline design and mission concepts.[1,2,3]

The *3CS* mission has four primary and three secondary objectives. The primary mission objectives include: stereo imaging, virtual formation flying, inter-satellite communications, and end-to-end command and data handling. The science will include imaging of clouds and other atmospheric structures using a satellite formation. After deployment, the three satellites will operate together using formation flying techniques. This will be accomplished while using virtual formation communications, a technology that allows the satellites to operate as a network utilizing communication and data links. Finally, the formation will use distributed and automated operations. This allows both individual nanosats and the entire formation to be reconfigured for optimum data gathering, command and control, and communication.

The secondary mission objectives include: validation of a MEMS heater chip for a free molecule micro-resistojet propulsion system, demonstration of generic nanosatellite bus design, and student education.

One of the principal features of the *3CS* mission is that all three nanosats are based on

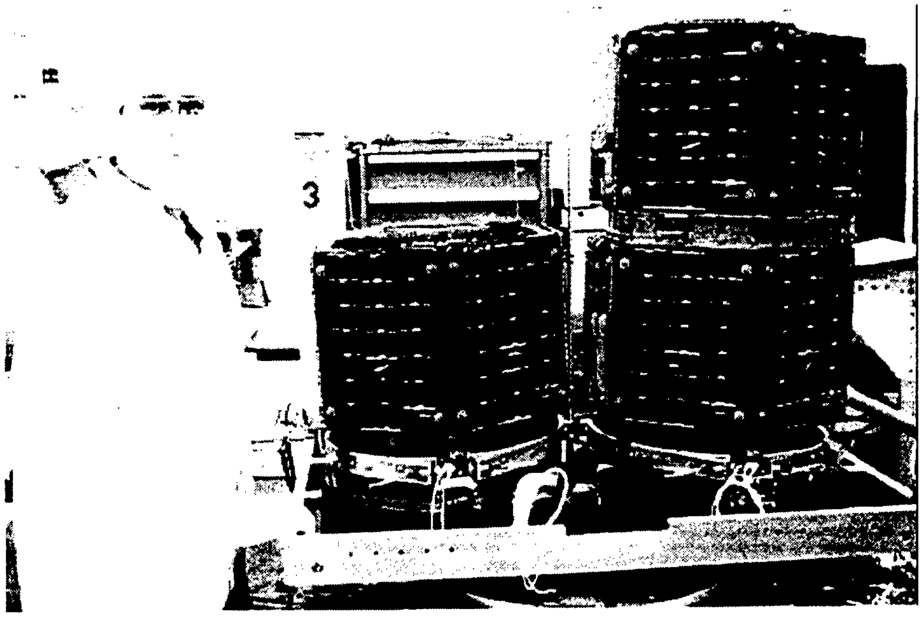


Figure 1 – Completed *3CS* nanosats in launch configuration.

a similar design. Each university has responsibility for different subsystems, and all components are designed to be common to each of the satellites. Each school's team is comprised of a faculty member and graduate and undergraduate students. Each school leads in its respective areas of expertise and on strengths proven on past projects as follows:

- ASU - program management, systems, structures, electrical power, micropropulsion, integration and testing, safety, configuration management and quality assurance
- CU - science (imaging), command and data handling, mission operations
- NMSU - communications

Using this team concept, the design was developed at the lead school with review and comment by the partner schools. In addition to the design work, the team members needed to verify that all components, materials, and design features would pass the NASA flight safety reviews for launch from the Space Shuttle. This paper concentrates on the design of the communications system that must operate with the overall cluster design and be produced to integrate with components developed at the other schools.

Design Considerations

To produce a flight radio system that would be usable across all three satellites, we needed to base the design on a tight set of constraints and design goals. The following paragraphs indicate the system constraints and the design goals for the flight radio.

Constraints

The largest constraint on the radio design was imposed by the power system. The total power budget for each satellite was expected to be approximately 10 W. From this, communications would be allocated 5 W from a regulated, 5-V power bus on a shared basis with other subsystems since communications would not be active at all times. The requirement for the radio system was that it operate with an input voltage of 5 V and draw no more than 1 A when operating. Due to inefficiencies and the slim power margins to begin with, it was not considered effective to use a DC-DC converter to raise the input voltage to a higher level.

The next constraint was that the radio system would need to support command services, downlink services, and inter-satellite services. The intention was to use the available allocations in the UHF and VFH bands, respectively, for the first two services. The inter-satellite service would be run as an amateur radio experiment utilizing packet radio and APRS techniques. The minimum data rate for the command and inter-satellite services would be 1200 bits per second while the minimum data rate for the telemetry data would be 9600 bits per second.

The solution for the flight radio system would need to meet the *3CS* size and weight constraints. While this never became a major issue, the overall design team tried to minimize weight whenever possible because the satellite stack was always close to its maximum allowed weight based on launch constraints.

Any system that was chosen would need to pass qualification testing. The radio system would be designed to survive the Hitchhiker vibration qualification testing.[4] The radio would also need to survive thermal cycles from -20° C to + 60° C.

One design constraint that was explicitly not imposed was for the components to be radiation hardened. This decision was made, primarily, because the expected lifetime of the satellites on orbit would be only a few months. Given this short expected mission lifetime, it was decided not to expend the extra cost for explicit radiation hardening. The project team decided that between having the radios mounted in aluminum boxes, the use of a redundant configuration, and the ability to reset the radios via the flight computer, the risk of total failure due to radiation effects would be small enough to warrant using commercial-grade parts.

Goals

The first design goal was to provide for all of the radio services in a single unit rather than having frequency-specific radios. This would help minimize weight and total power consumption. If a single radio could be used, a secondary design goal would be for the flight radio subsystem to provide a software control of frequency settings and radio parameters that would be under the control of the flight computer that would be scheduling operations. The final design goal was to provide for a redundant design to allow for a graceful failure of the flight radio subsystem.

Design Solution

The design of the flight radio was based on an existing commercially-available product. The following paragraphs describe why the components were chosen and how the components were modified for flight.

Radio Choice

Based on the design constraints, the Kenwood TH-D7 transceiver was chosen as the basis for the 3CS flight radio. The following features were key to selecting this particular model:

a. The radio would operate with a 5 V supply voltage and consume approximately 1 A of current at the highest power mode
b. The radio has two lower power settings thereby allowing for power control options

c. The radio has a standard RS-232 interface for data and control
d. The radio has an integrated modem thereby eliminating the need for an external modem. The radio also provided internal support for packet communications modes that can be customized by commands from the flight computer.
e. The radio could be easily modified for the UHF and VHF services required. The radio had built-in support for the inter-satellite link.

An additional feature that was found to be useful was that the TH-D7 stores its settings to memory so that they are not lost when the radio is powered off. This implies that the flight software does not need to re-load settings each time. However, this would remain an option to help recover from single-event upsets.

Because the basic radio components were relatively light when removed from the commercial housing, we proceeded to design a system with two TH-D7 units to form a redundant flight radio subsystem. The necessary modifications are next described.

Necessary Modifications

Because the TH-D7 was intended for a commercial market, it has a number of components that would either be unnecessary in a flight radio (speaker and microphone) or not allowed (zinc alloy plate and various plastics). By using an iterative process, a procedure was developed to exactly modify the radio to first maintain functionality and second to eliminate all components that were not necessary for flight or had to be modified to pass materials compatibility. The main materials problem was with the zinc alloy chassis plate used in the radio. This was replaced by an equivalent aluminum plate of the same form factor. The procedure was codified into a step-by-step procedure to be used in preparing the actual flight radios.[5] Figure 2 illustrates an exploded view of the initial radio components and the ones finally kept in the flight units. The circuit boards were conformal coated and held together with staking compound and lacing cord as shown in Figure 3. The main functional modification to the radio was to wire it to always to be "on" so that it would be operational whenever power was applied.

During testing of the radio's performance, we discovered that the manufacturer-supplied dual-band antenna did not perform well at VHF frequencies. The performance was 10 dB below that of a tuned blade antenna for the VHF frequency. We replaced the stock dual-band antenna with a different commercial dual-band antenna that was only 5 dB below the tuned blade performance at VHF and within 1 dB of tuned blade performance at UHF.

Redundant Design

One of the design goals was to produce a redundant flight radio sub-system for the *3CS* satellites. The design was realized by using two TH-D7's in a primary and backup configuration. Each radio would individually receive power only when the power sub-system was commanded to do so by the flight computer. Each radio was individually addressable by the flight computer through its RS-232 data port. Each radio uses its own dual-band antenna (no antenna cross switching). A Basic Stamp microcontroller was added to the design to ensure proper radio power up. Through testing, we found that on occasion, the TH-D7 would not properly initialize when power was first applied. The microcontroller monitors the input line to determine when the radios are powered. If the microcontroller detects that power has been applied to the radio but the radio does not

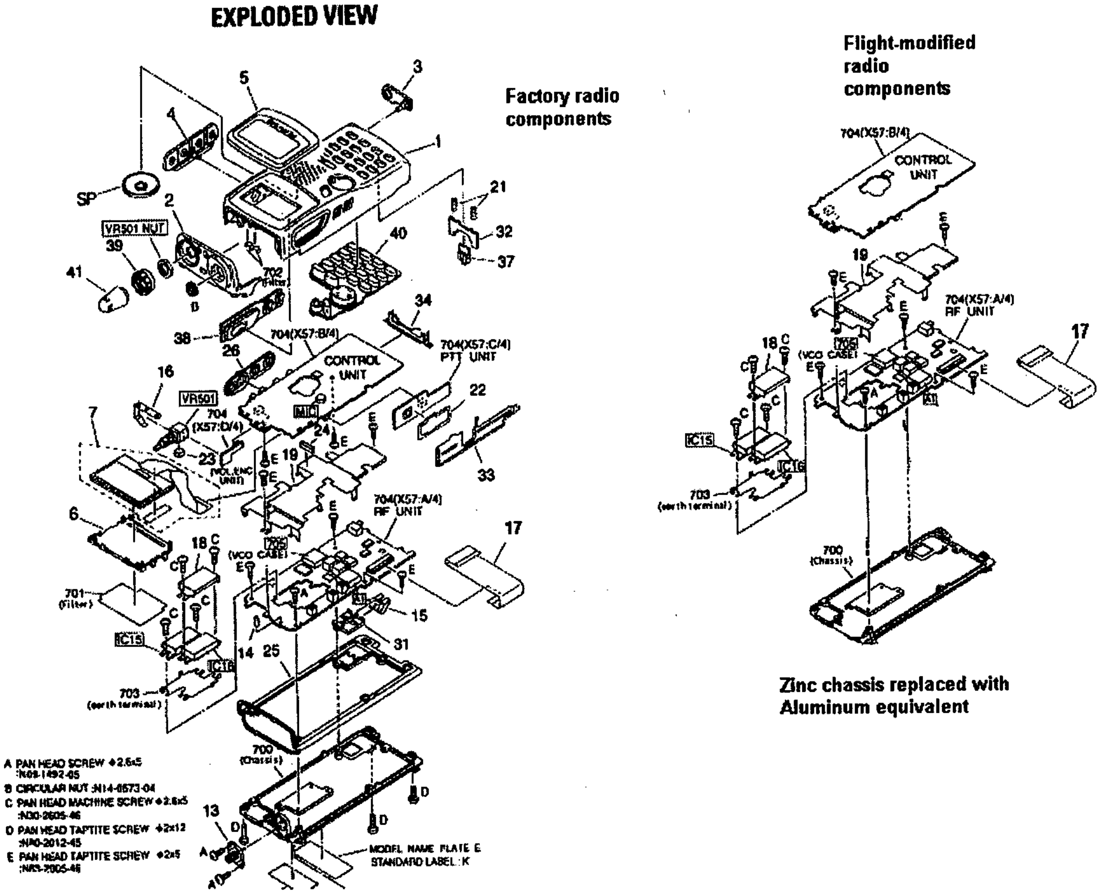


Figure 2 – Original TH-D7 components and the parts kept for the flight radio system

activate, then the microcontroller strobes the corresponding TH-D7 to emulate a user cycling the on/off switch. We have found that the radio will properly activate after this procedure. A separate circuit board was designed and fabricated for the microcontroller and added to the overall flight radio design.

Each subsystem in the *3CS* design is housed in its own aluminum box to provide low-level radiation shielding and to provide some radio frequency isolation and minimize interference between subsystems. The flight radio is no exception. The housing for the flight radio was designed to hold both TH-D7 radio circuit boards and the microcontroller circuit board. After assembly, the radio units were delivered to ASU for integration with the other satellite components.

The wiring diagram for the redundant configuration is illustrated in Figure 4 and one of the flight units being assembled with its aluminum housing is illustrated in Figure 5. A manual for the integrated design was produced to guide software developers and for operations training.[6]

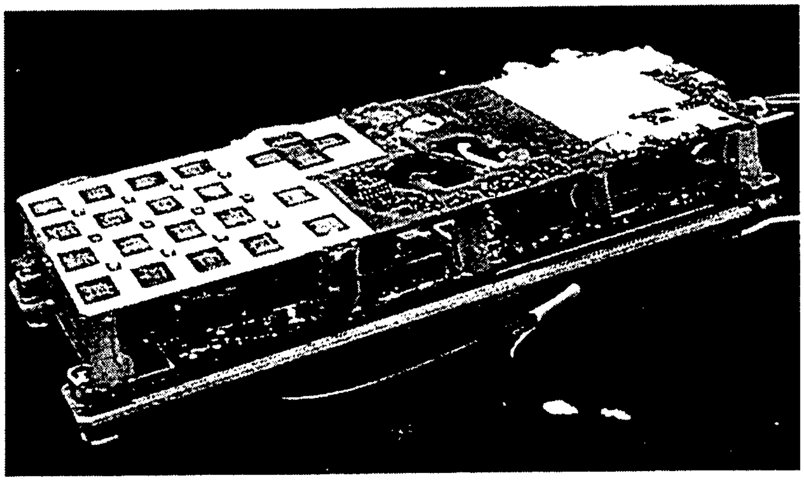


Figure 3 – Modified TH-D7 circuit boards that are conformal coated and use staking compound to separate the boards.

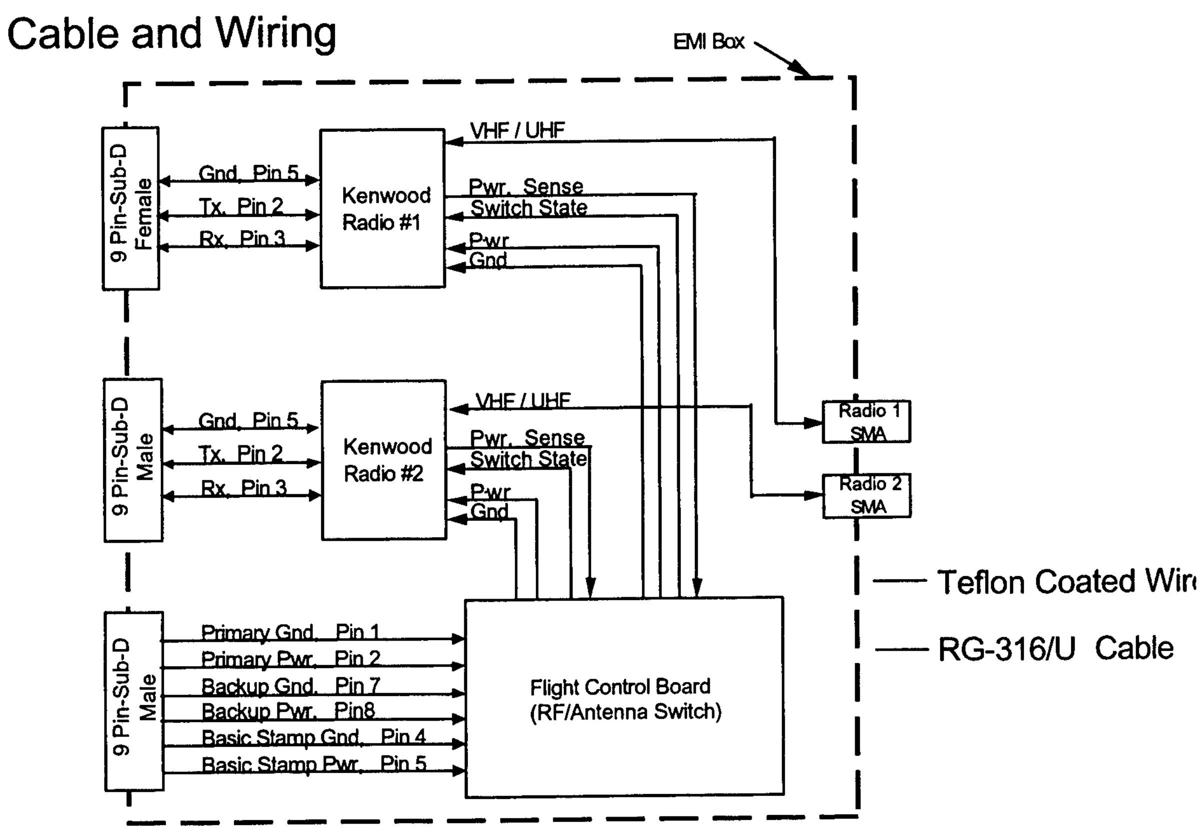


Figure 4 – Wiring diagram for the flight radio subsystem.

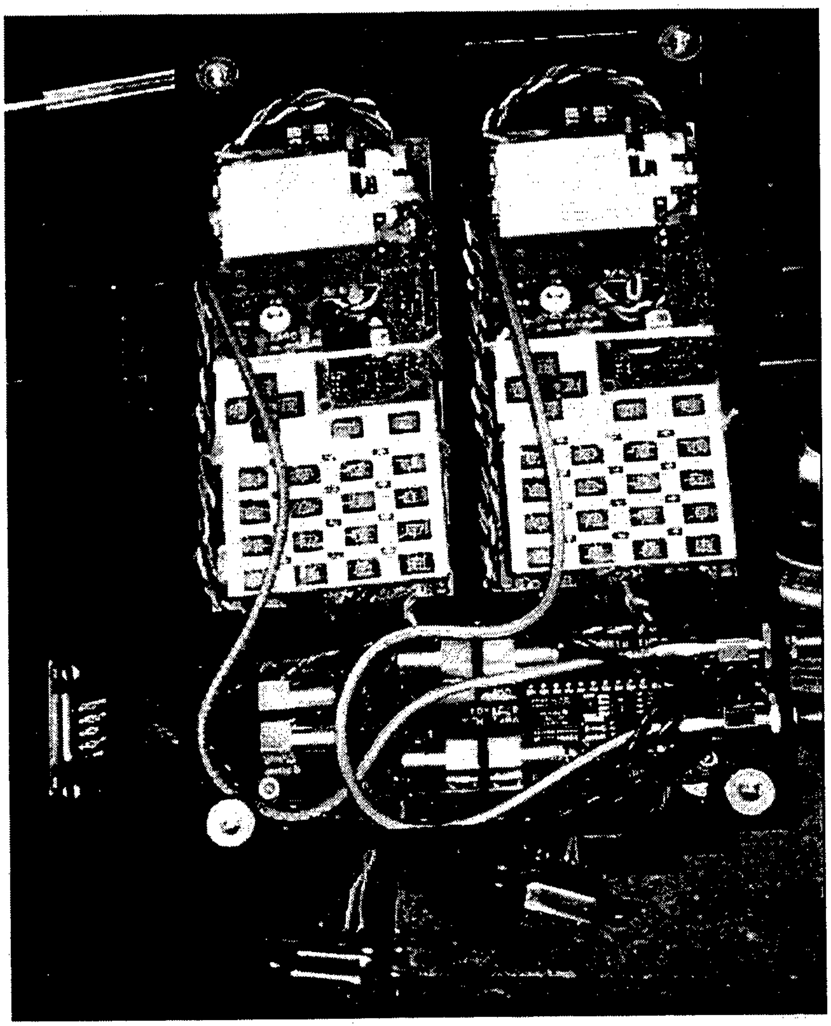


Figure 5 – Flight radio unit undergoing final assembly into aluminum housing.

Design Validation and Testing

To validate the design, an extensive test program was developed to ensure that no functionality was lost as the radios were modified, assembled into the flight units, and then delivered for integration into the satellite. The first step in the process was to start with the Manufacturer's Acceptance Test Plan where the required functions were tested, operational voltage and power confirmed, and radio transmission format and power were validated.[7] This test was derived from extensive experimenting with the radio's performance and developing automated scripts that would exercise the radio's set up and configuration. This test became the baseline for subsequent functional and characterization testing. The test sequence was also used to illustrate how the radios could be programmed for the software development team. After the electronics on each TH-D7 were modified, and before assembling into the flight unit, the individual unit was tested for proper functionality. This test was then performed again after flight unit assembly. This test procedure could then be re-run after other testing to validate proper functionality.

To validate that the flight radio would pass acceptance testing, an engineering unit was produced and subjected to thermal cycle testing and vibration testing. The vibration testing was at full shuttle qualification levels. A visual inspection and a test for proper functionality were performed after the vibration testing to ensure that the units survived.

Finally, a link analysis was performed to ensure that link closure would be possible with the radio system.[8] While link closure is possible, it may not be possible to downlink an entire uncompressed image during a single pass to a single ground station. It may be required to have several ground stations receive the image segments and then re-integrate the image in software.

Lessons Learned

One goal of the *3CS* program is to educate and have cooperation between the students at all three universities. We believe that such a goal was very much a major part of the program so far. In this section we will examine some of the lessons learned from the process of developing the communications sub-system for the *3CS* program.

Distributed Project Environment

By the very nature of a university, the students will come and go on a project. Sometimes this happens every few months. With the *3CS* program, this was happening across three universities that are geographically separated as well. By using teleconferences and the Web, information can be shared on frequent basis and updated rapidly so that the distance between universities is not a big problem. One lesson from this distributed environment is that documentation such as users' manuals need to be developed as early in the process as possible. These help the team members at other locations to learn the design and see how the design will begin to integrate with other subsystems. This can also assist in software development. As the design process iterated and changes were made, the manuals could be updated and distributed over the Web in near real-time to keep all team members current.

Testing and Documentation

While testing is required to show that a part is functioning properly or to validate performance, it is also useful as a training method. As students cycled through the program, we used detailed testing procedures to teach them how the radio units worked and what type of performance to expect. A corollary to this is that spare test units need to be procured because the test units are often broken as new personnel learn the test procedures.

From our experience, most students are not taught formal testing procedures in their laboratory classes. Therefore, the formal testing of the radios introduces the students to formalized and methodical procedures. Prior to problems occurring, we have generally found the students' attitudes to be that formal procedures are not really necessary. After the problem occurs, they see that the formal procedure can assist the engineer in finding the fault and verifying that the problem resolution has worked.

We also used the detailed testing to capture design mistakes. In one case, it forced us to re-design the antenna interface and change some of the operational philosophy for the satellite. This was caught before the flight radio units were delivered and integrated with the rest of the satellite.

Manufacturer Support

The manufacturer's distributor may be the least knowledgeable about the details of the components in the device. This is important both for materials and for operating characteristics. We encountered difficulties in determining the materials properties of certain components on the TH-D7. We eventually were able to track down the original manufacturer to obtain some of the information. It was necessary to conformal coat the component to ensure that it would pass NASA safety criteria. A similar problem was encountered with the intermediate frequency filter bandwidth specification for the radios that are required to complete the DD 1494 forms. In this case, the part needed to be located in the original manufacturer's catalog to obtain the specifications. The lesson learned for both cases is that the user will often need to reverse engineer a part to complete the paperwork necessary for flight. Adequate time needs to be placed in the schedule for these types of unanticipated activities.

Conclusions

A commercial-grade device can be readied for space flight and tested to pass basic safety and materials concerns. The usual engineering lessons of adequate documentation, well-specified procedures, and traceable performance become especially important when teaching students and when performing a distributed design. As might be expected, more time is actually spent on this type of paperwork activity than on actual design work. However, good documentation and good practices make the ability to work together across school boundaries an achievable goal.

Acknowledgments

This work was funded under grant F49620-99-1-0194 from the US Air Force Office of Sponsored Research, grant NAG5-9523 from NASA Goddard Space Flight Center, and additional NASA support via USRA.

References

1. Underhill, B., et al. "Three Corner Satellite Constellation – Arizona State University: Management; Electrical Power System; Structures, Mechanism, Thermal and Radiation; Attitude/Orbit Determination and Control; ASU Micropropulsion Experiment; and Integration," Proceedings of the 13th Annual AIAA/USU Conference on Small Satellites, SSC99-III-1, Logan, UT, August, 1999.
2. Hansen, E., et al. "Three Corner Sat Constellation: C&DH, Stereoscopic Imaging, and End-to-End Data System," Proceedings of the 13th Annual AIAA/USU Conference on Small Satellites, SSC99-IV-1, Logan, UT, August, 1999.
3. Horan, S., et al., "Three Corner Satellite Constellation – New Mexico State University: Communications, LEO Telecommunications Services, Intersatellite Communications, and Ground Stations and Network," Proceedings of the 13th Annual AIAA/USU Conference on Small Satellites, SSC99-VI-7, Logan, UT, August, 1999.
4. National Aeronautics and Space Administration, *Hitchhiker Customer Accommodations & Requirements Specifications*, 740-SPEC-008, Goddard Space Flight Center, 1999.
5. Horan, S., Alvarez, L., and Silva, A., "Assembly Procedure - Dual Transceiver,"

UN2-PLN-31114-417, Rev. a, Las Cruces, NM, 2001.
6. Horan, S., Alvarez, L., Anderson, B., Pachecho, R., and Jourdan, M., "Dual Transceiver User's Manual," UN2-MAN-31114-404, Rev.B, Las Cruces, NM, 2002.
7. Horan, S., Alvarez, L., Jourdan, M., and Silva, A., 'Manufacturers' Acceptance Test Procedure," UN2-RPT-31114-423, Rev.a, Las Cruces, NM 2001.
8. Horan, S., "3 Corner Satellite Communications Link Estimates," UN2-RPT-31114-403, Rev.a, Las Cruces, NM, 2000.

Stephen Horan received an A.B. degree in Physics from Franklin and Marshall College in 1976, an M.S. degree in astronomy in 1979, the M.S.E.E degree in 1981, and the Ph.D. degree in electrical engineering in 1984 all from New Mexico State University.
From 1984 through 1986, he was a software engineer and systems engineer with Space Communications Company at the NASA White Sands Ground Terminal where he was involved with the software maintenance and specification for satellite command and telemetry systems, and operator interfaces. In 1986 he joined the faculty at New Mexico State University where he is presently a Professor and holder of the *Frank Carden Chair in Telemetering and Telecommunications* in the Klipsch School of Electrical and Computer Engineering. His research and teaching interests are in space communications and telemetry systems.
Dr. Horan is the author of *Introduction to PCM Telemetering Systems* published by CRC Press. He is also a Senior Member of both the IEEE and AIAA, and a member of Eta Kappa Nu.

Lawrence Alvarez received a B.S. in Engineering Technology in December 1989 from New Mexico State University. In 1990, he worked briefly with Shay/Blythe International designing and fabricating laser diode controllers and Faraday Anomalous Dispersion Optical Filters. In 1991, he started at New Mexico State University and assisted in creating the Laser Communications Lab where he helped develop deep space laser communication systems funded by the Jet Propulsion Lab. Since 1994, under funding from NASA, he joined the Space & Telemetry Center as a Systems Technician. Here he continues to assist in research for space and wireless communications. He is co-author on numerous conference presentations and technical reports.

The *Three Corner Satellite* Mission

Stephen Horan and Lawrence Alvarez
Klipsch School of Electrical and Computer Engineering, Box 30001, MSC 3-O
New Mexico State University, Las Cruces, NM 88003-8001
Email: shoran@nmsu.edu; Phone: (505) 646-4856; FAX: (505) 646-6417

Michael Schoenoff, Lauren Egan, Assi Friedman, Michael Motola, Johan Carlson,
Darcy Allison, Erik Henrikson, Daniel Horner,
Lisa Tidwell, Michael Tilly, Joyce Wong, and Helen Reed
Mechanical and Aerospace Engineering, Engineering Research Center Room 342, Box 87-6106,
Arizona State University, Tempe, Arizona, 85287-6106
Email: helen.reed@asu.edu; Phone: (480) 965-2823; FAX: (480) 965-1384

Jen Michels, Stephan Esterhuizen, Matt Gadda, Steve Levin-Stankevich,
Alvin Ortiviz, Brian Egaas, and Elaine Hansen
Colorado Space Grant, University of Colorado at Boulder
Engineering Center Rm. 1B72, Boulder, CO 80309-0520
Email: Elaine.hansen@colorado.edu; Phone: (303) 492-3141; FAX: (303) 492-5456

ABSTRACT – *The Three Corner Satellite constellation is a cluster of three nanosats to be flown as part of the US Air Force University Nanosat program. This paper describes the mission objectives, the mission design approach, the satellite components, and the means for command and control of the mission elements. The satellites were completed and delivered in 2002 and are awaiting launch from the NASA space shuttle.*

1 - INTRODUCTION

The Three Corner Satellite (3CS) constellation is a cluster of three nanosatellites that are part of the US Air Force University Nanosat program. The 3CS project was begun in January 1999 and the cluster of satellites is presently awaiting launch in 2003 from the Space Shuttle. The satellites are shown in their launch configuration in Fig. 1. The 3CS project is a joint effort of the faculty, staff, and students at the participating universities: Arizona State University (ASU), the University of Colorado at Boulder (CU), and New Mexico State University (NMSU). Consult the [Unde 99], [Hans 99] and [Hora 99] for further details on the baseline design and mission concepts.

The 3CS mission has four primary and three secondary objectives. The primary mission objectives include: stereo imaging, virtual formation flying, inter-satellite communications, and end to end command and data handling. The science will include imaging of clouds and other atmospheric structures using a satellite formation. After deployment, the three satellites will operate together using formation flying techniques. This will be accomplished while using virtual formation communications, a technology that allows the satellites to operate as a network utilizing communication and data links. Finally, the formation will use distributed and automated operations. This allows both individual nanosats and the entire formation to be reconfigured for optimum data gathering, command and control, and communication.

The secondary mission objectives include: validation of a MEMS heater chip for a Free Molecule

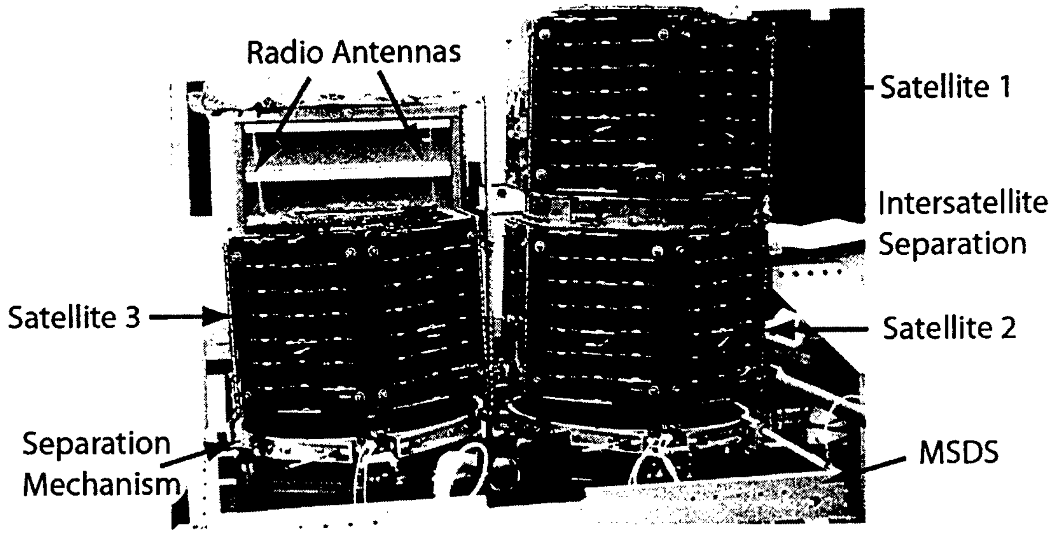


Fig. 1 - Three Corner Satellite launch configuration.

Micro Resistojet (FMMR) propulsion system, demonstration of generic nanosatellite bus design, and student education.

One of the principal features of the 3CS mission is that all three nanosats are based on a similar design. Each university has responsibility for different subsystems, and all components are designed to be common to each of the satellites. Each school's team is comprised of a faculty member and graduate and undergraduate students. Each school leads in its respective areas of expertise and on strengths proven on past projects as follows:

a. ASU - program management, systems, structures, electrical power, micropropulsion, integration and testing, safety, configuration management and quality assurance,
b. CU - science (imaging), command and data handling, mission operations, and
c. NMSU - communications

Using this team concept, the design was developed at the lead school with review and comment by the partner schools. In addition to the design work, the team members needed to verify that all components, materials, and design features would pass the NASA flight safety reviews for launch from the Space Shuttle. This paper concentrates on the design of the satellites. Since the individual subsystems were produced by different partner members at each school, the overall set of components needed to be matched and integrated at final assembly.

2 - SATELLITE SUBSYSTEMS

The 3CS satellites were designed and fabricated as three common satellites. The main differences are antenna placement, the inclusion of the FMMR test electronics on two cluster members, and some additional solar cells on one satellite. In this section, we will describe the common components for each satellite necessary for the formation flying mission goals. This includes the structure, the power system, the end-to-end data system, the imaging system, and the communications system.

2.1 - Structure

The structure for each satellite is based on a machined 6061-T6 aluminum isogrid structure as illustrated in Fig. 2. The structure is hexagonal in cross section with the major axis for the satellite

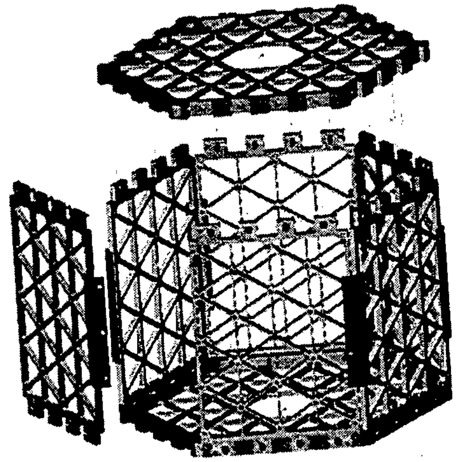


Fig. 2 - Isogrid structural components.

being 44.7 cm and the minor axis for the satellite is 39.4 cm. The height of each satellite is 29.2 cm. As can be seen in Fig. 2, the side panels and the top and bottom plates form an interlocking structure. Brackets are added where the side panels abut for increased rigidity. The aluminum is anodized except for electrical contact points. The side and top panels are the load-bearing structure for the satellite. The structure was tested to verify that it would meet required strength and vibration mode requirements for a space shuttle payload.

2.2 - Power Electronics

The Electrical Power System (EPS) is composed of the following elements

a. solar cells,
b. battery pack,
c. inhibit relays,
d. DC/DC converter, and
e. microprocessor controller.

The system elements are organized as illustrated in Fig. 3. The power from the battery and the solar cells is distributed as +5 V regulated and +12 V unregulated power. The 12-V power is used by the cameras and imaging electronics. The 5-V power is for other components. All systems but EPS have in-line switches controlled by EPS to prevent power-on prior to safe operating conditions being established after launch and to control the satellite power budget. The EPS microcontroller is a PIC microcontroller with a watchdog timer. The EPS microcontroller is responsible for

a. sampling and storing health and welfare telemetry measurements,
b. listening for end-to-end data system commands to enable/disable individual components, and
c. acting as a watchdog timer for the end-to-end data system.

The inhibit relays are required to prevent premature energizing of the electronics during launch. There are three latching relays between each power source and the load. There is also one latching relay in the ground leg for each power source. These relays are set by the inhibit timer electronics in the MSDS portion of the launch configuration.

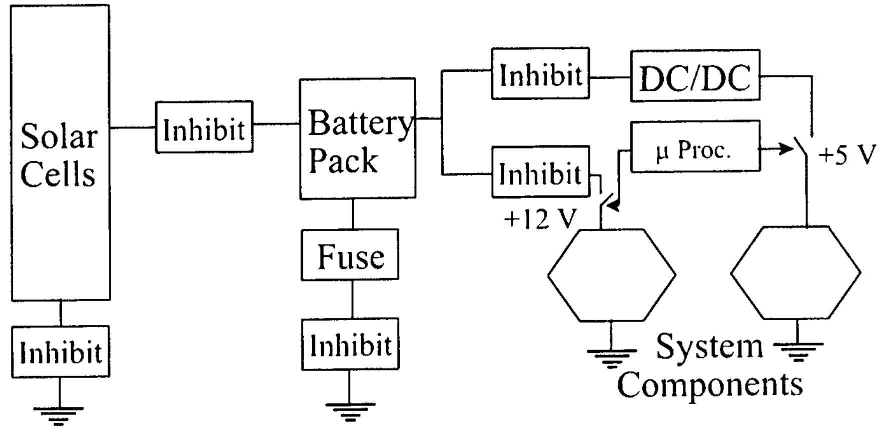


Fig. 3 - Electrical power system components.

The solar panels use dual-junction gallium arsenide solar cells that are commercially manufactured. The side panels and top panel of each satellite holds the solar panel structure in place. Each panel consists of two strings of nine cells with each cell generating approximately 2.4 V. The solar panel contains a current meter and diode protection. The solar panel configuration is shown in the left half of Fig. 4

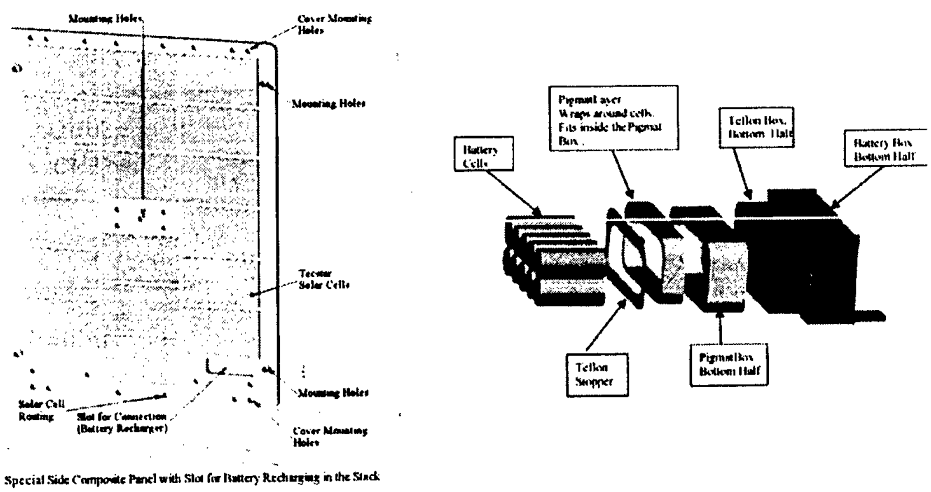


Fig 4. - Electrical Power System components: solar cell panel and battery.

The battery portion of the EPS is composed of a pack of ten NiCd cells with 2300 mAh of capacity. The battery is illustrated in the right half of Fig. 4 which shows the packaging into a vented box with absorbent material to mitigate any leakage effects.

2.3 - End-to-End Data Systems

The End-to-End Data System (EEDS) is an integration of computer hardware, software, procedures, and personnel for cluster command and control and data handling. The hardware component in each satellite includes an 823 Power PC flight computer having 16 MB of RAM, 8 MB of RAM organized as a solid state recorder, and a critical decoder for processing initialization commands.

The software is stored on disk and in ROM. The flight software is disabled until after deployment from the MSDS. The software uses a commercial operating system (VxWorks) and extensive use of commercial software tools for controlling the satellites. The primary tool is the System Control Language (SCL) to program rules to monitor the health and welfare of the satellite. The current state of the satellite can initiate scripts to take counter measures for detected faults. The rules can also be used to generate scripts to perform specific functions, e.g. initialize the radio system or the imaging system. Operational science events such as taking a sequence of pictures are also SCL-based activities.

The command structure for the satellites is based on specific files sent from the ground stations, inter-satellite messages, and pre-stored, timed commands. The scheduling software can build a sequence of operational commands to be executed between ground station contact times.

2.4 - Imaging

The imaging system for the satellites is based on four cameras per satellite with the goal of producing images of clouds from orbit. There are two cameras on the top bulkhead and two cameras on the bottom bulkhead. The cameras interface with EEDS for data and EPS for power. The cameras are commercial cameras using a 640 x 480 pixel CMOS sensor. The cameras have full automatic exposure control. The on-board algorithms will be used to evaluate image quality and prioritize the images for downloading. The imaging cameras are illustrated in the right portion of Fig. 5 and the mounting in the bulkhead in shown in the left portion of Fig. 5.

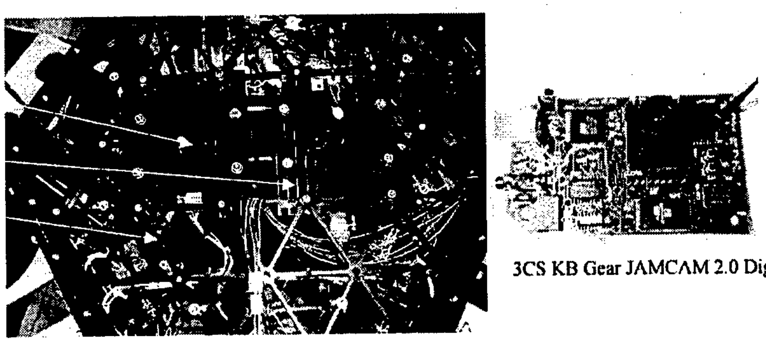


Fig. 5 - Imaging system: placement on the satellite and the digital camera in the imaging system.

2.5 - Communications

The communications system is based on commercial amateur radio hardware that has been modified for an extended frequency range outside the amateur bands. The radios are arranged as a dual redundant flight radio in each satellite. Each radio is software programmable via the EEDS to set frequency, power, and operating characteristics. The radios are only powered on when supplied power by the EPS to help control the overall satellite power budget with each radio being individually powered. The nominal operating mode will be to have one radio on at all times in receive mode to listen for commands. The radios use a VHF frequency for the data downlink, UHF frequency for the command uplink, and a different UHF frequency for the inter-satellite crosslink communications. All communications use a frequency shift keying technique and the AX.25 packet communications protocol at the physical channel level. The data rates available on the radios are 1200 bps and 9600 bps. The maximum transmission power is 1 W.

The antenna system uses a commercial dual-band antenna for each radio. The antennas on the two satellites that are joined in the 2 x 1 launch configuration have their antennas inserted into a sheath inside the other satellite for launch. Upon satellite separation, the antennas are withdrawn from the sheaths without use of a deployment mechanism.

The primary ground control station will be at CU. The other schools (ASU and NMSU) will have compatible ground stations to be used as backup relay points for both commands and telemetry by using store and forward data files in either direction. The uplink data files can be commands, schedules, or revised software. The relationship between the satellites and the ground stations is illustrated in Fig. 6.

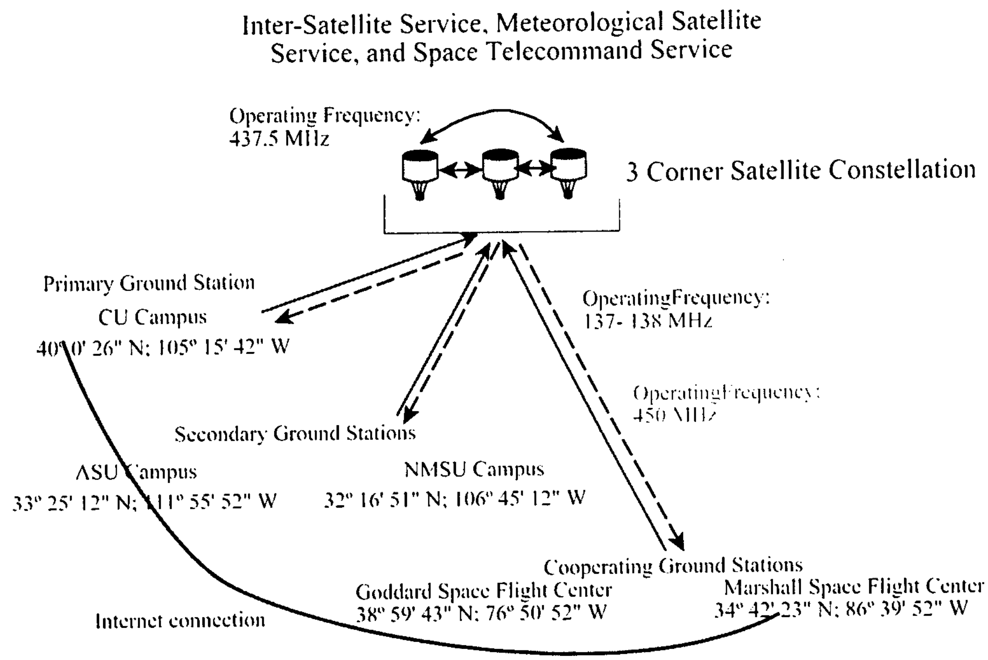


Fig. 6 - Line diagram of communications frequencies and ground stations.

3 - LAUNCH CONFIGURATION

The satellite cluster launch configuration was shown in Fig. 1. The 2x1 satellite configuration was determined by vibration limits on the satellite separation systems. This configuration consists of

a. the individual satellites
b. the Lightband inter-satellite separation mechanism between the two joined satellites
c. the Starsys separation mechanism between the launch plate and the satellite on it
d. the Multiple Satellite Deployment System (MSDS) that holds the cluster configuration.

For the purposes of this project, the Lightband, Starsys, and MSDS components are "government furnished equipment" and outside the control of the 3CS project team. However, the satellites need to be compatible with the components. Additionally, the timer control and power for removing the inhibits are controlled through the MSDS electronics. The electronic signals for activating the satellites are passed through the Starsys and Lightband components to the cluster members. This integrated system is delivered to NASA to be mated with the NASA systems for launch.

4 - FORMATION FLYING

The satellite cluster was designed to meet a virtual formation mission. That is, the cluster performance was designed to be based on relative position knowledge and not on relative position control. The mission science goal of stereoscopic imaging is based on using software and knowledge of the satellite position from the orbital elements to generate the composite image from the individual satellite images. Another mission goal of distributed operations is facilitated by the use of inter-satellite communication links to provide the means for controlling the satellite cluster by being able to relay commands from a ground control station through one satellite to another satellite. The communications internal modem also has a short messaging service that can be used in conjunction with the normal packet communications modes to relay messages between the satellites for command and control by the flight computer software.

ACKNOWLEDGMENTS

This project was supported by grants through the Air Force Office of Sponsored Research and the National Aeronautics and Space Administration's Goddard Space Flight Center to the individual schools. Each school also raised supporting funds from internal sources and numerous industry sponsors.

REFERENCES:

[Unde 99] Underhill, B., et al. "Three Corner Satellite Constellation - Arizona State University: Management; Electrical Power System; Structures, Mechanism, Thermal and Radiation; Attitude/Orbit Determination and Control; ASU Micropropulsion Experiment; and Integration," *Proceedings of the 13th Annual AIAA/USU Conference on Small Satellites,* SSC99-III-1, Logan, UT, August, 1999.

[Hans 99] Hansen, E., et al. "Three Corner Sat Constellation: C&DH, Stereoscopic Imaging, and End-to-End Data System," *Proceedings of the 13th Annual AIAA/USU Conference on Small Satellites*, SSC99-IV-1, Logan, UT, August, 1999.

[Hora 99] Horan, S., et al., "Three Corner Satellite Constellation - New Mexico State University: Communications, LEO Telecommunications Services, Intersatellite Communications, and Ground Stations and Network," *Proceedings of the 13th Annual AIAA/USU Conference on Small Satellites,* SSC99-VI-7, Logan, UT, August, 1999.

NETWORKING SATELLITE GROUND STATIONS USING LABVIEW

Kendall Mauldin
New Mexico State University

ABSTRACT

A multi-platform network design that is automated, bi-directional, capable of store and forward operations, and low-bandwidth has been developed to connect multiple satellite ground stations together in real-time. The LabVIEW programming language has been used to develop both the server and client aspects of this network. Future plans for this project include implementing a fully operational ground network using the described concepts, and using this network for real-time satellite operations. This paper describes the design requirements, RF and ground-based network configuration, software implementation, and operational testing of the ground network.

KEY WORDS

Space Telemetry, Satellite Networking, Scalable Networking, Ground Station

INTRODUCTION

Small satellites known as "Nano-sats" are more commonly being designed and built by small organizations and research institutions. There exists a need for a scalable, reconfigurable ground station network for use by these smaller organizations that may not have the time or money to design their own full-scale, multi-site satellite ground station network. For such a network to be easily useable by small research projects, the bulk of the network design should be already done. The network must also be scalable to be able to adapt to the needs of the particular Nano-sat project. To demonstrate this, a specific Nano-sat project called "3 Corner Sat" will be used as an example.

The "3 Corner Sat" (3CS) project is part of the AFOSR/DARPA University Nanosatellite program. It is a joint effort between Arizona State University, University of Colorado at Boulder, and New Mexico State University. The project is building a constellation of 3 satellites that will perform tests on new types of Nano-sat technology such as stereo imaging of cloud and land formations, formation flying, and new types of command and control scheduling. Because of the nature of the constellation and communication system configurations, a custom design for the ground station communications network is needed.

This paper will discuss a means of constructing such a ground network using the LabVIEW™ version 6 software suite developed by National Instruments™. The network is comprised of two different Multi-platform Virtual Instruments (VIs). These VIs were designed to be compatible with many computing platforms and operating systems. In this paper, we will examine the design goals for this ground network, the server/client configuration, the data interaction between the server and client, selection of a programming environment for implementation, and the virtual instruments that were created to complete the design.

GROUND NETWORK DESIGN GOALS

The ground network has several key design requirements that are defined by the nature of the satellite configuration. These requirements were not able to be met with the use of conventional, commercially available satellite networking systems. Thus, a new ground network system will be designed and tested with the following requirements in mind:

1) The ground communications network shall support a minimum of three remote ground stations from a control station.
2) The ground communications network will provide a means to remotely initialize each remote ground station.
3) The ground communications network will provide a means to monitor the status of the remote ground stations.
4) The ground communications network will provide data transfer between each remote terminal and the central control station.
5) The data transfer function will include the ability for store-and-forward of bi-directional data.
6) The store-and-forward data transmission will have the means to send data from the control station to each remote terminal for later transmission to the satellites.
7) The store-and-forward data transmission will have the means to record satellite data at each remote terminal for later transmission to the control station in the event that the internet link goes down.
8) The control station and the remote terminals shall have synchronized clocks
9) The ground communications network shall have security measures that protect against unauthorized use of the system
10) The ground communications network software will be capable of execution on current Windows (98/NT/2000/XP), Unix, Macintosh, and Linux operating systems.

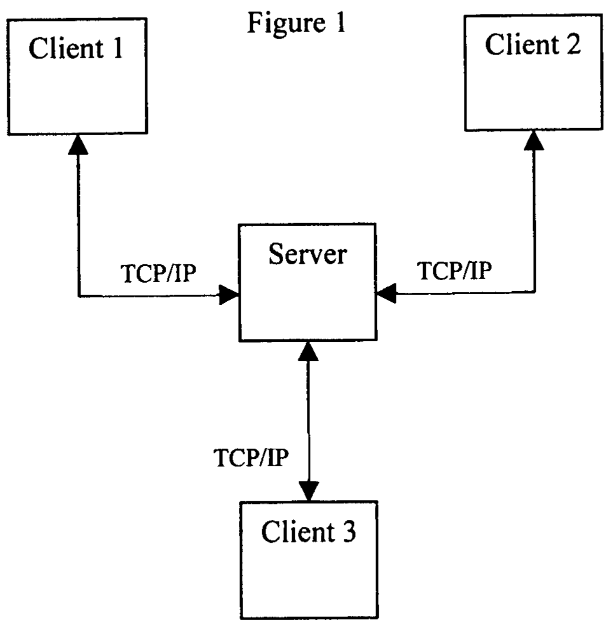
It is the goal of the 3CS communications team to meet all design requirement expectations by using new, innovative implementation methods. These methods will allow such a ground network system to be customizable for future Nano-sat or similar projects.

GENERAL IMPLEMENTATION

The ground network will consist of one "Server" and multiple "Client" systems. The server and client labels that are given to these stations describe the nature of operation and data flow present at that location. The server will consist of one computer at the Nano-sat mission control center. This station is responsible for all data that is distributed to the constellation, and collected from the constellation. It is also responsible for the operation of the individual ground communication stations. The client will consist of a computer running at each of the ground stations. This client will act as a conduit for all information that is to pass to or from the satellite constellation. It is also responsible for control of antenna movement to be able to track satellites across the sky during a pass.

It is desirable to have all client stations collaborating to be able to schedule operations based on satellite passes. For example, one of the ground stations may have a better vantage point for communications to the satellite constellation than the other ground stations. For this reason, all satellite communications are done through that ground station for that particular pass, until another station becomes a better candidate. The station with the best accessibility to the satellite constellation is determined by the personnel at the mission control center, who will have satellite pass prediction software aiding them in their decision. The communication connection between the clients and server are made by using standard TCP/IP sockets over the internet. This allows the client stations to be anywhere in the world, theoretically.

Figure 1



SERVER IMPLEMENTATION

The program that runs on the server computer was developed using the LabVIEW™ version 6 software suite developed by National Instruments™. This development environment allows graphical construction and modifications of executable programs called "Virtual Instruments" (VI). See figure 2 for an example. A VI was created that performs several tasks:

1) Disperses data that is to be transmitted to the satellite cluster to a specific ground station or multiple ground stations.
2) Receives live or stored data from ground stations that has been received from the satellite constellation.
3) Provides a Graphical User Interface (GUI) to personnel at mission control, allowing them to control ground station network operations at each individual ground station, and the network as a whole. Figure 3 displays the front panel of this GUI.
4) Provides an internet-based interface to other mission control computers for real-time data acquisition and analysis.

Figure 2: An example of an actual VI's source code.

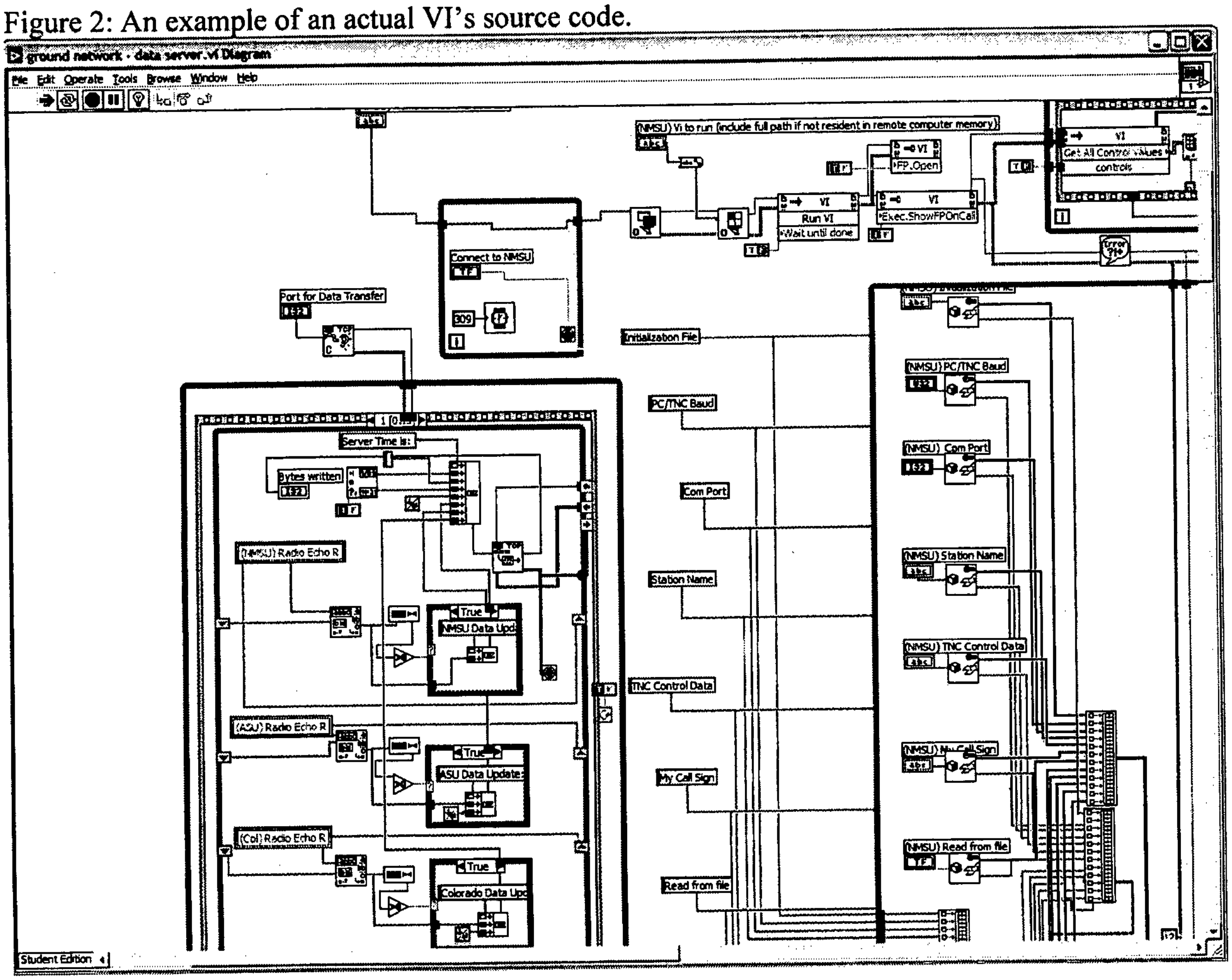
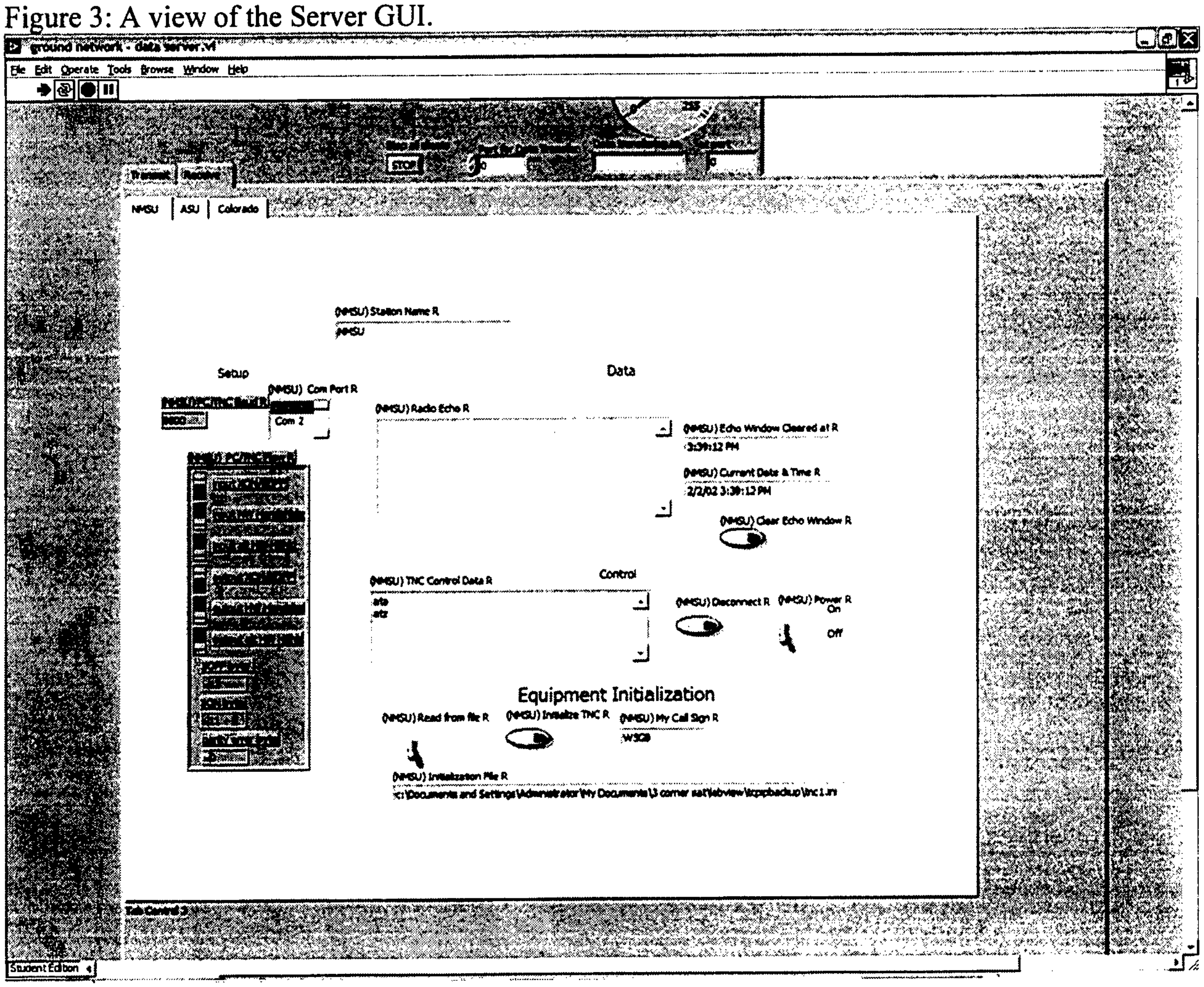


Figure 3: A view of the Server GUI.



The server is programmed to communicate with the clients using a LabVIEW communications driver that is running on the client computers in parallel with the client VIs. This driver is called the "VI Server". It allows other VIs that are running at another location to control the local VI, and also to receive data from the local VI. The VI Server drivers use a standard TCP/IP internet connection as the communication backbone.

The data received from the clients by the server is split into two categories: Satellite data and VI display data. The VI display data is extracted and used to generate displays on the server computer that are identical to each of the displays on the client computers. These displays are updated approx every 2-3 seconds. The satellite data then remains, and is made available for other computers in the mission control center to acquire via a standard TCP/IP telnet connection. For simplicity, the data that comes from the individual ground stations is tagged as being from a particular station, but is not recombined by the server computer. The tagged data is combined by another mission control computer based on the needs of the mission control team.

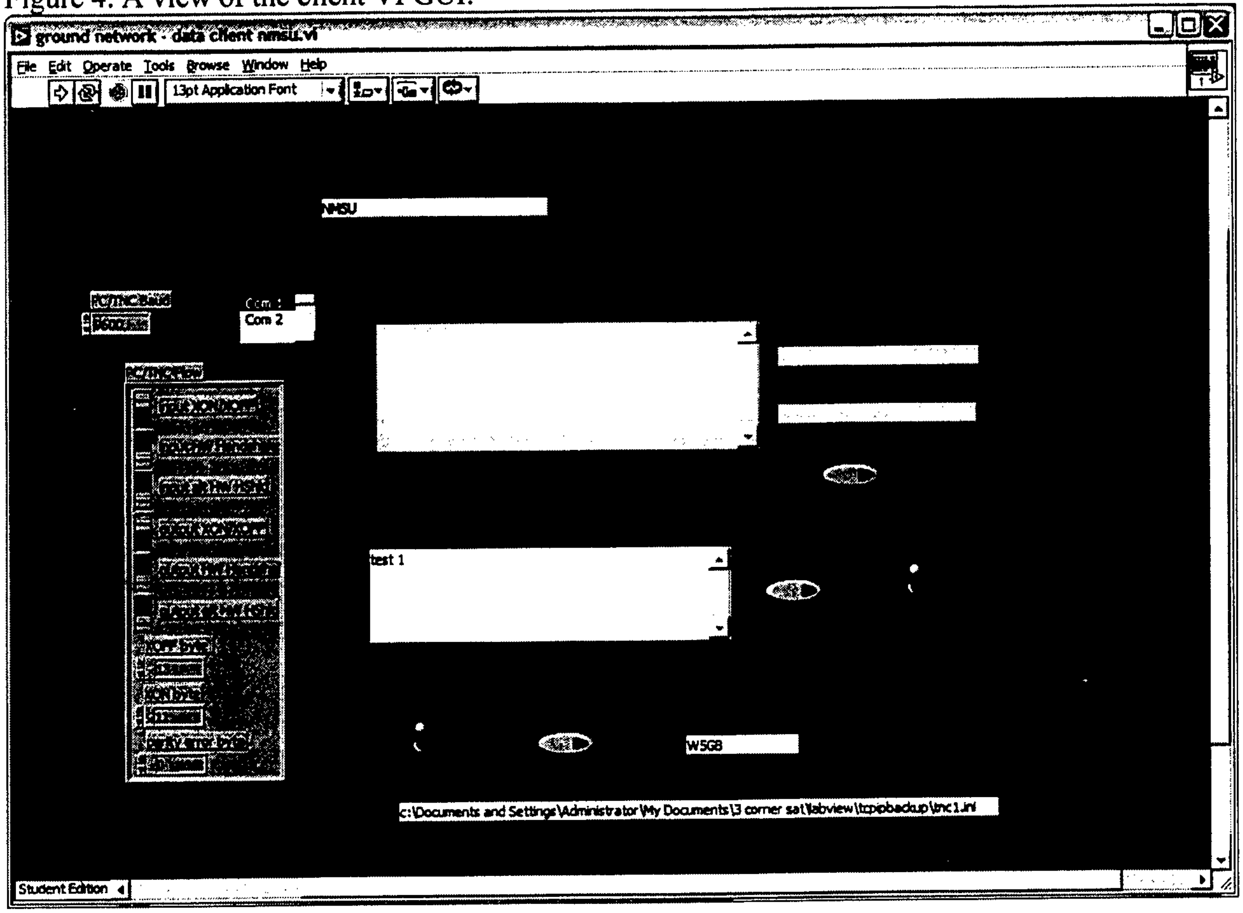
The data transferred from the server to each of the clients is categorized in a similar fashion. There again exists two types of data: Ground station control data, and satellite data (commands, etc.) to be transmitted. The ground station control data is generated by the GUI on the server display. For example, if a mission control team member clicks on a graphical toggle switch on the server display that is associated with the client at NMSU, the matching button gets toggled on the client computer itself. The satellite transmit data is generated not by the server, but by other mission control computers. This data is merely relayed by the server to the appropriate client(s) as defined by mission control personnel.

CLIENT IMPLEMENTATION

The client computer is running at the site where the actual ground satellite communications hardware is located. The computer is connected to ground station hardware that transmits and receives data to/from the satellite constellation. The computer is also connected to a standard full-time internet access point. The program that runs on the client computers is also a VI. This VI performs the following tasks:

1) Relays data from the server at mission control to the satellite ground communications radio hardware.
2) Relays data from the satellite ground communications radio hardware to the server computer at mission control.
3) Transmits health and status of client VI and ground station equipment to mission control.
4) Receives commands from mission control to change client VI or ground station equipment operation.
5) Stores data in the case that a portion of communications is cut off between client and satellites or client and mission control server computer. The data is forwarded when communications are re-established.
6) Provides a graphical user interface (GUI) at the ground station location for on-site control of the client VI in case of emergency operation. See Figure 4 for a view of this GUI.

Figure 4. A view of the client VI GUI.



The "VI Server" driver that was mentioned above, is running in parallel with the client VI. The driver is managing communications with the server VI via standard TCP/IP methods. The driver then separates the two types of data that is coming from the server computer. The ground station control command data is extracted and used to modify client VI operational settings. The data that is intended for the satellite cluster is passed along to the client VI as raw data. This raw data is then relayed to the ground station communications hardware.

In a sense, the same TCP/IP socket connection is being used for both raw satellite data, and ground station command and control data. This reduces the complexity of the connection that is required between the ground stations and mission control. Any reduction in complexity from the mission control standpoint will allow mission control personnel to focus on flight operations instead of how the data will be transferred to/from the satellite constellation.

CONCLUSION

A scalable, reconfigurable, and automated ground network system is a desirable feature of many satellite projects. In the case of university-based Nano-sat programs, a fairly limited budget and limited amount of manpower puts a great importance on efficiency and simplicity of the systems that are used. In the case of the 3 Corner Sat program, the capabilities that this ground network system will give the project will help insure the success of the mission. In this example, we are using an off-the-shelf product to create an acceptable solution to the logistical problems that accompany a satellite project that uses multiple ground communication stations. The 3CS communications team hopes that this ground network design might be helpful to other Nano-sat or similar programs that are in need of such system.